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THESIS

ANALYZING AND PREDICTING UNDERWATER HULL COATING SYSTEM WEAR

by

James R. Wimmer

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Thesis Advisor: Lyn R. Whitaker

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The coating system of an aircraft carrier's underwater hull consists of two layers, an anti-corrosive under layer and an anti-fouling upper layer. The anti-fouling layer is a soft paint designed to ablate, continuously releasing toxins to inhibit marine growth. This feature causes the anti-fouling layer to wear over time and with hull cleaning. Sufficient anti-fouling paint needs to be applied so that the anti-fouling layer remains effective through a ship's operational cycle until the next dry-docking availability. The NSTM guidelines for how much anti-fouling paint should be applied are inadequate. NSTM fails to recognize that paint is not applied uniformly and that wear of the anti-fouling layer is also not uniform. Difficulties in implementing the guidelines are compounded by the fact that the anti-fouling layer cannot be measured directly. We propose a remedy for this situation. A simple method for estimating the distribution of the thickness of the anti-fouling layer is given, based on measurements of the coating system before and after the anti-fouling layer is applied. In addition, a model is fit based on data from five aircraft carriers collected over ten years that predicts the change of the total coating thickness as a function of the number of years at sea, number of hydro-washes and number of underwater hull cleanings. This model is simple, fits the data, and has been tested on an independent set of data. This model can be used to help decide how much anti-fouling paint should be applied so that it continues to prevent fouling of an aircraft carrier hull for a projected operational/maintenance cycle.

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ANALYZING AND PREDICTING UNDERWATER HULL COATING SYSTEM WEAR

James R. Wimmer
Lieutenant, United States Navy
B.S., United States Naval Academy, 1991

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Author: James R. Wimmer
James R. Wimmer

Approved by: Lyn R. Whitaker
Lyn R. Whitaker, Thesis Advisor

R. R. Read
Robert R. Read, Second Reader

Frank C. Petho
Frank Petho, Chairman
Department of Operations Research

ABSTRACT

The coating system of an aircraft carrier's underwater hull consists of two layers, an anti-corrosive under layer and an anti-fouling upper layer. The anti-fouling layer is a soft paint designed to ablate, continuously releasing toxins to inhibit marine growth. This feature causes the anti-fouling layer to wear over time and with hull cleaning. Sufficient anti-fouling paint needs to be applied so that the anti-fouling layer remains effective through a ship's operational cycle until the next dry-docking availability. Naval Ship Technical Manual (NSTM) guidelines for how much anti-fouling paint should be applied are inadequate. NSTM fails to recognize that paint is not applied uniformly and that wear of the anti-fouling layer is also not uniform. Difficulties in implementing the guidelines are compounded by the fact that the anti-fouling layer cannot be measured directly. We propose a remedy for this situation. A simple method for estimating the distribution of the thickness of the anti-fouling layer is given, based on measurements of the coating system before and after the anti-fouling layer is applied. In addition, a model is fit based on data from five aircraft carriers collected over ten years that predicts the change of the total coating thickness as a function of the number of years at sea, number of hydro-washes and number of underwater hull cleanings. This model is simple, fits the data, and has been tested on an independent set of data. This model can be used to help decide how much anti-fouling paint should be applied so that it continues to prevent fouling of an aircraft carrier hull for a projected operational/maintenance cycle.

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LIST OF ABBREVIATIONS

NSTM	Naval Ship Technical Manual
DFT	Dry film thickness
PERA	Planning and Engineering for Repairs and Alteration command
CV	Conventionally powered aircraft carrier
CVN	Nuclear powered aircraft carrier
cdf	Cumulative distribution function
T	Total coating system thickness random variable
AC	Anti-corrosive sub-system thickness random variable
AF	Anti-fouling sub-system thickness random variable

EXECUTIVE SUMMARY

A ship's underwater coating system is comprised of multiple coats of anti-fouling paint applied on top of multiple coats of anti-corrosive paint in order to protect the hull from both marine growth and corrosion. A fouled hull, while not as catastrophic as a corrosion failure, is the more likely type of failure and profoundly affects a ship's performance. Excessive marine growth disrupts the smooth laminar flow of water along a ship's hull and significantly increases drag. As a result, a ship's speed and fuel efficiency are significantly decreased. The anti-fouling paints used by the US Navy since 1985 to combat marine growth are designed to slowly and continuously ablate, releasing a toxin that inhibits marine growth on a ship's hull. Due to the relatively short period of time in use, little information is known about the wear characteristics of these anti-fouling paints over extended periods of time.

With the estimated cost of replacing an entire underwater hull coating system approaching three million dollars for many US Navy ships, increased effort is being placed upon extending the service life of coating systems and reusing existing coating systems through multiple operational cycles. However, to accomplish these goals, sufficient anti-fouling paint must be applied to protect the ship's hull from fouling, as well as to ensure that the coating system remains in a salvageable state in order to reuse it during the ship's next operational cycle. Current US Navy hull maintenance guidelines, promulgated in NSTM, incorrectly assume uniform paint application and uniform wear over time. Moreover, NSTM only considers total coating thickness and not the anti-fouling sub-system thickness. As a result, these guidelines are ineffective. Analytical tools capable of estimating the anti-fouling thickness distribution and predicting coating system wear as a function of operational cycle duration and hull maintenance frequency are needed.

This thesis proposes that the anti-fouling sub-system be evaluated directly in addition to the total coating system thickness. Since the anti-fouling sub-system cannot be measured directly, an estimate of the anti-fouling sub-system thickness distribution is used. By measuring the anti-corrosive sub-system and total coating thickness, a

deconvolution may be performed to estimate the thickness distribution of the anti-fouling sub-system. A simple *ad hoc* method is presented, affording a more detailed analysis of the anti-fouling sub-system.

Using total coating thickness data collected since 1985, a qualitative analysis of total coating system wear is performed. The impact of hull maintenance procedures, previously assumed to be negligible, are shown to have more impact on an underwater hull coating system than six years of routine operations at sea. It is also discovered that the changes to a coating system's quantiles are roughly linear for both operational cycle duration and maintenance procedures. This finding permits the effective use of a least squares regression to develop a model capable of predicting coating system wear. This model is tested on an independent data set and predicts total coating system wear remarkably well for this particular ship's coating system.

As a result of this model, a coating system may now be evaluated with respect to the ship's projected operational cycle and hull maintenance requirements while the ship is still in drydock and additional paint may still be applied. This model may have the potential to improve coating system serviceability and increase the probability of reusing a coating system through multiple operational cycles. Thus, millions of dollars associated with coating system removal and replacement are saved.

I. INTRODUCTION

The US Navy spends about 300 million dollars per year associated with drydocking ships, of which approximately 80 million dollars is directly attributed to hull preservation [Ref. 1]. To help reduce hull husbandry and drydocking expenditures, there is increased effort to both extend the service life of underwater hull coating systems and "reuse" existing coating systems through multiple operational cycles. However, to accomplish these goals, improvements must be made to current hull maintenance guidelines. Moreover, the effect of an operation cycle and hull maintenance on the coating system of a US naval vessel is not fully understood. Thus, existing US Navy hull maintenance policy as stated in the Naval Ship Technical Manual (NSTM), directs that all naval ships receive essentially the same underwater hull coating system, without consideration to its expected duration of operation or its anticipated hull maintenance requirements[Ref. 2].

The current coating system has been used by the US Navy since 1985. Since then, the Planning and Engineering for Repairs and Alterations command for US Navy aircraft carriers, PERA(CV), has been closely monitoring hull coating systems for all aircraft carriers. The hull coating system for each aircraft carrier is closely inspected and evaluated during every drydocking. In many cases, the hull coating inspection reveals that the coating system is still capable of protecting the hull from corrosion and excessive marine growth and simply requires additional paint. For those hull coating systems that are determined to be in a salvageable condition, typically less than one hundred thousand dollars worth of minor repairs and additional coats of paint is required to successfully extend the existing coating system's service life through the next drydocking opportunity. By simply repairing and applying additional coats of paint to an existing coating system, millions of dollars in paint removal expenses are eliminated. The key is to apply sufficient paint at each drydocking so that coating systems are salvageable at the ship's next drydocking. This is particularly important as the intervals between drydockings are lengthened from approximately seven years up to twelve years. Using paint dry film thickness (DFT) data collected by PERA(CV) during their inspection of underwater coating systems of aircraft carriers, this study provides both qualitative insight and

quantitative tools to assist in answering the following questions: Will a specific underwater coating system be able to adequately persevere for a given period of time with a given number of hull treatment procedures? And, if not, how many additional coats of paint are required to ensure that a coating system can safely withstand a given operational schedule? [Ref. 3]

A ship's underwater coating system is comprised of multiple coats of anti-fouling paint applied on top of multiple coats of anti-corrosive paint in order to protect the hull from both marine growth and corrosion. A severe corrosion failure may cause structural damage to the hull that may ultimately result in a loss of watertight integrity below the waterline. A fouled hull, while not as catastrophic as a corrosion failure, is the more likely type of failure and profoundly affects a ship's performance. Excessive marine growth on a hull disrupts the smooth laminar flow of water along a ship's hull and significantly increases drag. This requires more force to propel the ship through the water and puts additional strain on the propulsion system. Consequently, the ship's maximum speed is reduced while significantly increasing its fuel consumption in order to overcome the increased resistance. To illustrate the impact of marine fouling upon naval warfare, it is estimated that the US Navy spends between 75 to 100 million dollars per year in propulsive fuel to overcome the effects of marine fouling induced drag on ship hulls [Ref. 1].

The anti-fouling paints currently used by the US Navy to combat this severe problem are designed to slowly and continuously leach cuprous oxide, a toxin that prevents marine growth from living on the exterior of a ship's hull. To maintain a high concentration of cuprous oxide on the surface, these anti-fouling paints are designed to slowly wear away as the ship moves through the water, continuously exposing "fresh" paint with a high concentration of toxin. Since these anti-fouling paints must ablate in order to be effective and are applied as the outermost layer of a coating system, the manner and rate of wear for these anti-fouling paints are a determining factor in the expected service life of a coating system and the focus of this thesis. However, since the US Navy has only been using these ablative anti-fouling paints since 1985, there is limited data available pertaining to the wear characteristics of these ablative paints over extended

periods of operation at sea. Consequently, there has been no significant analysis concerning the wear characteristics of these ablative paints on US Navy ships during actual operational conditions. Anti-fouling paint wear is currently assumed to be negligible.

This study includes both qualitative and quantitative analysis of the distribution of paint thickness and wear rates of an underwater hull coating system. In Chapter II, the distribution of the thickness of a freshly applied coating system is analyzed in some detail to provide a "baseline." Because the thickness of the anti-fouling paint system cannot be measured directly, this section also gives a method for estimating the distribution of anti-fouling paint thickness from the distribution of the total paint thickness and the anti-corrosive paint thickness. In Chapter III, paint ablation is examined as a function of time at sea, hull cleanings, and hull hydro-washes. A mathematical model to predict the distributions of a coating system's paint thickness as a function of time, as well as the number and type of hull maintenance procedures is developed in Chapter IV. This model is used to evaluate whether an anti-fouling coating subsystem is sufficient to survive in a salvageable condition through the ship's next operational cycle. Chapter V will conclude this analysis with a discussion and recommendations.

II. COATING SYSTEM PROPERTIES AND EVALUATION TECHNIQUES

An underwater hull coating system consists of two main sub-systems: an anti-corrosive system and an anti-fouling system. The anti-corrosive system usually consists of two coats of International 5806 series paint applied directly on top of a single, thin coat of Devoe 201 anti-corrosive paint. The anti-corrosive paint system works in conjunction with the ship's impressed current or sacrificial anode cathodic protection system. These systems work independently to ensure that minimal corrosion occurs below the waterline. The anti-fouling system typically contains three coats of anti-fouling paint applied directly on top of the anti-corrosive coating system. The two types of anti-fouling paints currently used by the US Navy are International BRA 540 series and Devoe ABC-3 series. Both of these paints are designed to ablate slowly, continuously exposing a paint surface with a high concentration of cuprous oxide, a toxin that prevents marine organisms from growing on the hull coating system. The paint characteristics and wear rates of these two types of anti-fouling paints are assumed to be identical by the United States Navy and no distinction is made between the two paint types throughout this study.

A. HULL COATING THICKNESS AT INITIAL APPLICATION

An initial underwater coating system consists of multiple coats of anti-corrosive and anti-fouling paints applied to a hull that has been sand-blasted to "white" metal. Table 1 gives the required thickness for each coat, as prescribed by NSTM, Chapter 631.

	Coating Type	Thickness
1st coat	Devoe 201 (epoxy primer)	2-3 mils
2nd coat	International 5806/5807 (anti-corrosive paint)	5 mils
3rd coat	International 5806/5807 (anti-corrosive paint)	5 mils
4th coat	Int'l BRA 540/2 or Devoe ABC-3 (anti-fouling paint)	4 mils
5th coat	Int'l BRA 540/2 or Devoe ABC-3 (anti-fouling paint)	4 mils
6th coat	Int'l BRA 540/2 or Devoe ABC-3 (anti-fouling paint)	4 mils

Table 1. NSTM prescribed coating system.

Each coat of paint is applied manually using spray guns while the ship is in dry-dock. Due to factors such as environmental conditions, the experience level of the painters, location of

scaffolding and obstructions, a coat of paint cannot be applied uniformly at its prescribed thickness in a shipyard environment. In reality, the thickness of a single coat of paint varies considerably within a very small area of just a few square inches. Moreover, the variability of a coating system's thickness increases as each additional coat of paint is applied.

Data collected by PERA(CV) is used to demonstrate the large variability in coating thickness immediately after application. This data consists of dry film thickness (DFT) measurements collected from randomly selected locations on the hulls of three aircraft carriers. Typically, each data set contains DFT measurements collected immediately before or after a ship's operational cycle or maintenance procedure, such as a hydro-washing or hull cleaning. Table 2 gives the summary statistics of paint thickness for the hull coating systems of USS Forrestal (CV 59,) USS Nimitz (CVN 68) and USS Lincoln (CVN 72) immediately following application.

Ship	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum	Sample Size
USS Nimitz (CVN 68)	8.3	21.9	27.9	28.2	34.1	72.9	2099
USS Roosevelt (CVN 72)	7.7	26.6	32.1	33.4	39.2	82	4095
USS Forrestal (CV 59)	10.6	29.1	33.8	34.3	38.8	63.2	3030

Table 2. Summary statistics of three freshly applied coating systems.

Note the large ranges of paint thickness, 64.6 mils, 74.3 mils and 52.6 mils for CVN 68, CVN 72 and CV 59, respectively. In accordance with NSTM guidelines, each of these coating systems should be identical, with all DFT measurements falling between a total coating thickness of 24 to 25 mils.

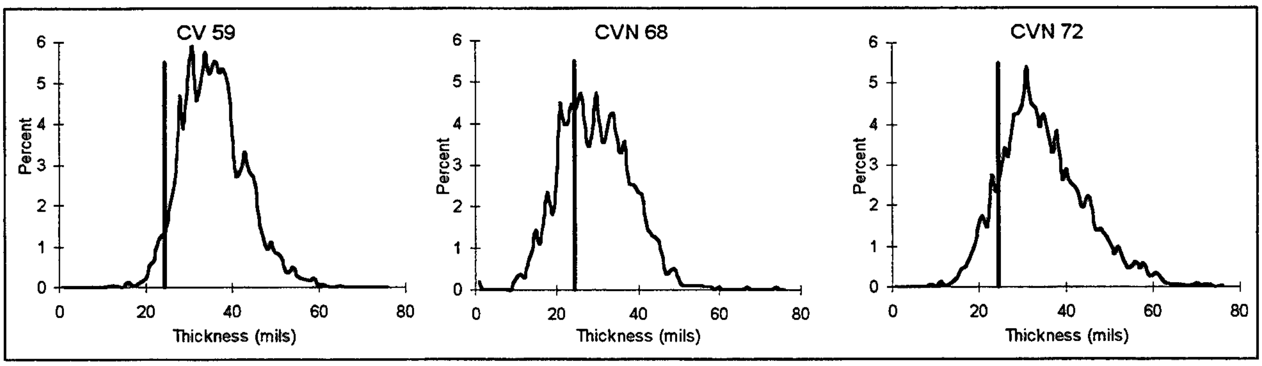

Figure 1. Hull coating system thickness following initial paint application. The vertical lines indicate the NSTM prescribed thickness (24-25 mils.)

However, from the frequency histogram in Figure 1, fewer than ten percent of each ship's DFT measurements actually fall within this range. For CVN 68, nearly 35 percent of all DFT

measurements are below the minimum desired thickness of 24 mils. In fact, over half of the DFT measurements are more than four mils, the prescribed thickness of a coat of anti-fouling paint, less than or greater than 24-25 mils. The exceptionally thin DFT measurements that result from current methods of paint application are present prior to any operating time at sea or hull treatment procedures. These measurements, represented by the left tail of the coating thickness distribution, ultimately play a critical role in determining the expected service life of a coating system.

B. COATING SYSTEM EVALUATION POLICY AND TECHNIQUES

In order for a coating system to protect the hull, its paint must be in sound physical condition and in sufficient quantity. The US Navy's requirements for evaluating a hull coating system, as set forth in NSTM Chapter 631, provide tremendous detail pertaining to the physical evaluation of the paint's material condition. Very specific instructions for assessing a coating system's physical blemishes, such as blistering, flaking and chalking, are given. NSTM also includes clear and concise criterion for determining when a hull coating system must be completely removed and replaced as a result of one of these material failures. On the other hand, with respect to the amount of paint, NSTM simply requires that a coating system meets the paint scheme given in Table 1. In practice, NSTM guidelines are checked by inspecting and taking DFT measurements after the entire coating system (both anti-corrosive and anti-fouling layers) is applied. Thus, NSTM is reduced to requiring a total paint thickness of 24-25 mils. This implicitly assumes that paint is applied uniformly over the entire hull. [Ref. 2]

1. Current Interpretations of NSTM

To compensate for the fact that paint thickness is not uniform, NSTM guidelines are interpreted in a variety of ways. They are most often interpreted to mean that either the mode, median, or average paint thickness measurement from randomly selected locations of the hull must be at least 24-25 mils. These measures of central tendency are potentially misleading, since they do not fully characterize the entire paint thickness distribution of a coating system. The large

variance of paint thickness typically yields a sample average that provides an overly optimistic depiction of a coating system. For example, CVN 68's coating system, shown in Figure 1, has an average DFT measurement of 28.2 mils even though nearly 38 percent of the hull possesses a coating system thickness less than 24 mils.

At the other extreme, during a hull coating inspection of USS Independence (CV 62) following an eight year operational cycle, a much more conservative approach was taken. In this particular case, NSTM guidelines were interpreted to mean that the minimum DFT measurement of each sample of coating thickness measurements taken from various locations on the hull must be at least 25 mils. During the inspection of CV 62, sets of 50 measurements were taken at 67 different locations on the hull. Sixty-four of the 67 locations had a minimum DFT measurement less than 25 mils. As a result, it was concluded that CV 62 's underwater hull coating system did not meet NSTM standards and additional paint was deemed necessary. [Ref. 4]

To illustrate the consequences of this approach, suppose that there is only a 0.06 probability, p, that a particular DFT measurement in a particular location is less than 25 mils. This choice of p is extremely conservative when compared to CVN 68's freshly applied coating system, where nearly 38 percent of its hull coating system is less than 24 mils (see Figure 1.) Assuming that the measurements taken at each location are independent, the probability that at least one DFT measurement at a specific location will fall below the desired 25 mils is

$$1 - (1 - p)^{50} = 1 - (1 - 0.06)^{50}$$

$$= 0.955.$$

If in addition, the inspection at different locations can be modeled as a sequence of 67 independent Binomial trials, then the expected number of trials containing a failing DFT measurement is

$$67 * 0.955 = 64.$$

This interpretation of NSTM would determine that there is insufficient paint for a coating system for which only six percent of coating is thinner than 25 mils. It would certainly lead to the same conclusion for all three of the freshly applied coating systems illustrated in Figure 1.

2. Fitting Distributions to Initial Hull Paint Thickness

It is clear that a standard evaluation technique is required to ensure consistent results. Since paint thickness distributions are asymmetric and possess large variances, care must be taken to adequately quantify these distributions. The thinnest areas of a hull coating system are the most vulnerable to ablative failure and represent the "weak link of the chain." Therefore, emphasis should be placed upon developing a method that adequately characterizes the left tail of the distribution of paint thickness. It is also important that computations for this method be relatively straight forward. One approach to evaluate the entire thickness distribution is to model a coating system with a particular family of distribution. It may be tempting to assume that the DFT measurements of a coating system are normally distributed and approximate the paint thickness with a Normal distribution. To graphically compare the three distributions of coating thickness to the Normal distribution, Figure 2 includes the frequency histograms of the three coating systems with plots of the Normal density superimposed.

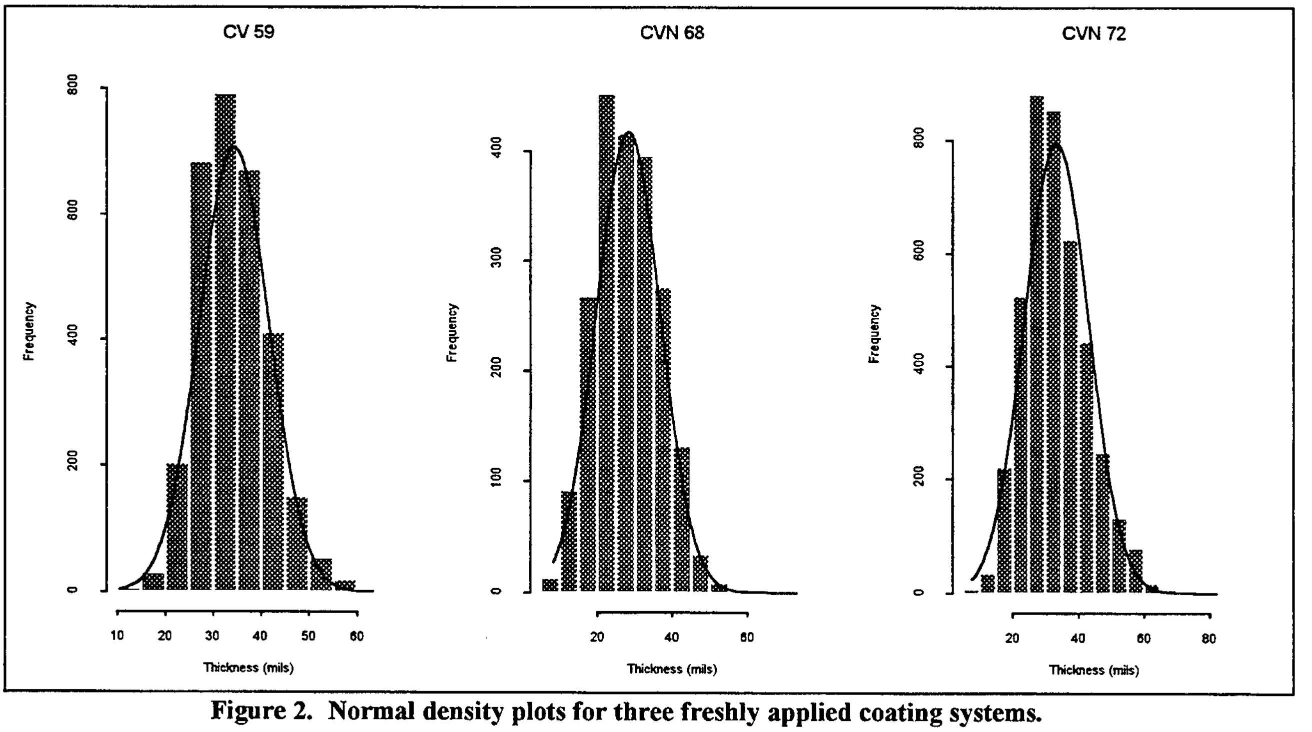

Figure 2. Normal density plots for three freshly applied coating systems.

The histograms indicate a "heavy" right tail for all three coating system. The positive skew shows up more clearly in the Normal Probability Plots for CVN 68 and CVN 72 in Figure 3.

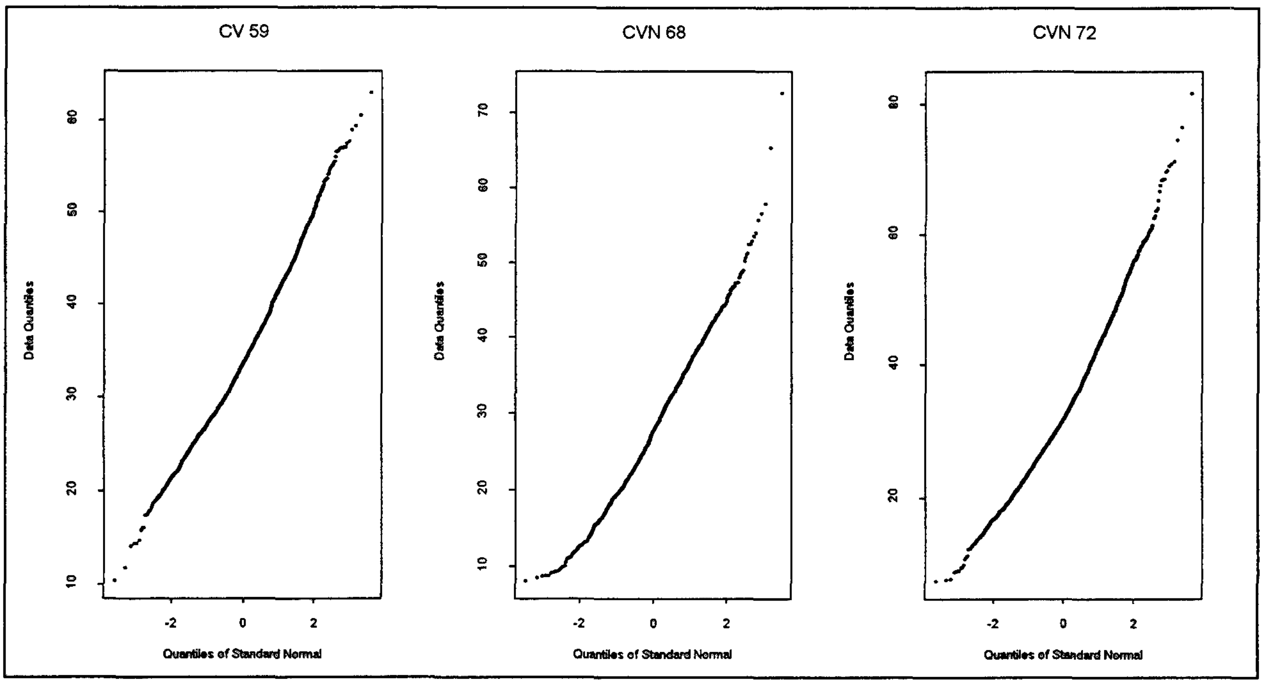

Figure 3. Normal probability plots for three freshly applied coating systems.

As suggested from the asymmetry of the data, illustrated in Figures 2 and 3, the Kolmogorov-Smirnov Goodness-of-Fit test rejects the null hypothesis of normality for CV 59, CVN 68, and CVN 72 with p-values less than 0.000001.

Other families of distributions, such as the Log-Normal, Gamma, and Weibull distributions are fit to the three data sets to determine if all three freshly applied coating systems may be consistently and adequately characterized by a single family of distributions. Since the Gamma distribution provides the best fit for two of the three data sets, the use of the gamma distribution to characterize all freshly applied coating systems is explored further. Gamma probability plots are provided in Figure 4.

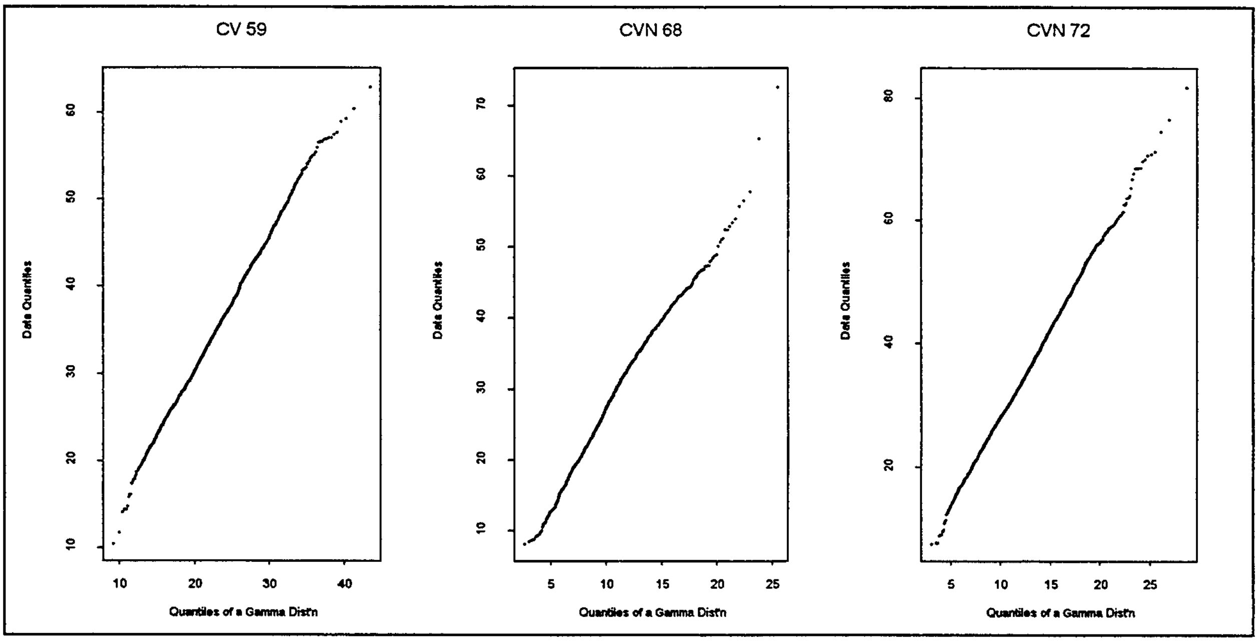

Figure 4. Gamma probability plots for three freshly applied coating systems.

The Gamma distribution provides a respectable fit for all three coating systems from a visual point of view. However, the Kolmogorov-Smirnov Goodness-of-Fit test rejects the null hypothesis that the distribution is Gamma with p-values less than 0.0001.

With such large sample sizes, a feasible alternative to the Gamma distribution is to use a nonparametric estimator for the distribution of hull paint thickness. The simplest nonparametric estimator is the empirical cumulative distribution function (cdf.) For any value x, the empirical cdf gives the proportion of measurements that are less than or equal to x. The empirical cdf has the advantage of direct computation. It also has the advantage of being robust to the shape of the true paint thickness distribution. This is important since there is no guarantee that other ship's paint thickness distributions can be adequately modeled by a Gamma distribution. The use of the Gamma distribution further entails finding the maximum likelihood estimators for its parameters for which there is no closed form. The empirical cdf's for CVN 68, CVN 72 and CV 59 are given in Figure 5.

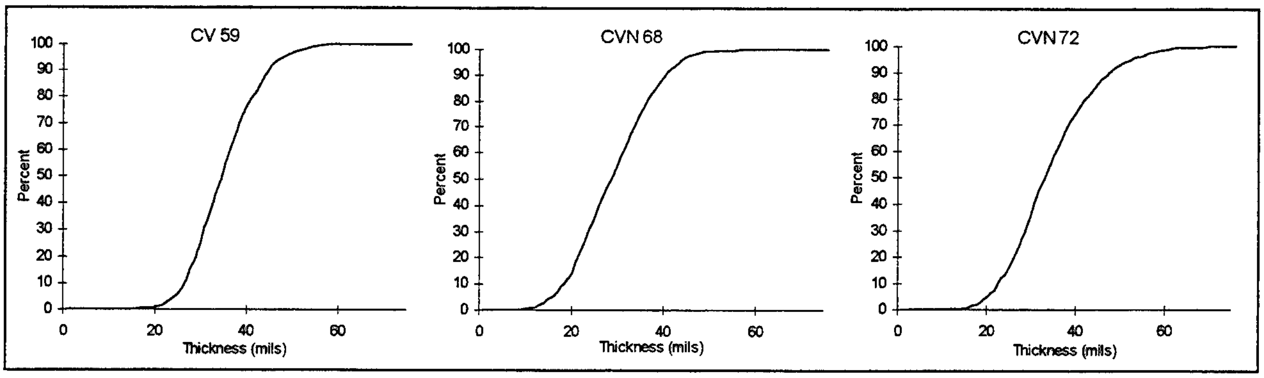

Figure 5. Empirical cdf's for three freshly applied coating systems.

C. ESTIMATING THE ANTI-FOULING DISTRIBUTION

The primary method of evaluating the condition of an underwater coating system is to collect DFT measurements of the total paint thickness from randomly selected locations on the hull. Since the anti-fouling sub-system minimizes hull fouling as well as protects the anti-corrosive paint sub-system underneath it, the composition of anti-fouling paint is a vital factor in a coating system's service life and must be considered. The most obvious method to determine anti-fouling thickness at a specific location is to measure the anti-corrosive paint thickness prior to applying the anti-fouling paint and then re-measure the total paint thickness at the exact same location after the anti-fouling paint is applied. The anti-fouling paint thickness is then the difference of these two measurements. However, with the vast area of an aircraft carrier's hull, it is virtually impossible to replicate the total thickness measurements at the precise location that the anti-corrosive measurements were taken. With the large variance in coating thickness, even a slight error in location may produce very different DFT measurements. Consequently, the distribution of the anti-fouling sub-system must be found from the distribution of the anti-corrosive sub-system and the distribution of total coating thickness.

Let the positive random variables T, AC and AF represent the total coating thickness, anti-corrosive paint thickness and anti-fouling paint thickness at a particular location. Then

$$T = AC + AF,$$

and it is reasonable to assume that AC and AF are independent. The distribution of T, F_T, is the convolution of F_{AC} and F_{AF}, the distributions of AC and AF, respectively. Therefore, the

distribution of AF is the deconvolution or decomposition of F_T and F_{AC}. Estimating F_{AF} is difficult. There are several approaches, and Medgyssey provides a comprehensive overview [Ref. 5]. More recent work is found in [Ref. 6] and [Ref. 7.] All of this work assumes parametric forms or symmetry for some or all of the distributions involved in the deconvolution. However, since we do not know whether F_{AC} can be modeled by a parametric family and Figure 1 suggests that F_T is not symmetric, we use the following *ad hoc* estimator for F_{AF}. Let T_{max} be the largest observed total coating thickness and $0 = a_1 < a_2 < \ldots < a_N = T_{max}$ be N equally spaced values between 0 and T_{max}. We will approximate F_{AF}, F_{AC} and F_T by discrete versions of these distributions. With this simplification and the independence of AC and AF:

$$
\begin{aligned}
F_T(a_1) &= F_{AC}(a_1)\,P(AF = a_1)\,, \\
F_T(a_2) &= F_{AC}(a_1)\,P(AF = a_2) + F_{AC}(a_2)\,P(AF = a_1)\,, \\
&\;\;\vdots \\
F_T(a_i) &= \sum_{j=1}^{i} F_{AC}(a_j)\,P(AF = a_{i-j+1})\,, \qquad (2.1) \\
&\;\;\vdots \\
F_T(a_N) &= \sum_{j=1}^{N} F_{AC}(a_j)\,P(AF = a_{N-j+1})\,.
\end{aligned}
$$

Replacing F_T and F_{AC} with the empirical cdf's $\hat{F}_T$ and $\hat{F}_{AC}$ and solving the system of linear equations (2.1,) we obtain estimates $\hat{P}(AF = a_i)$ of $P(AF = a_i)$ from which we can compute

$$\hat{F}_{AF}(x) = \sum_{\{i\,:\,a_i \le x\}} \hat{P}(AF = a_i)\,.$$

This estimator is *ad hoc*. If large samples are used to compute $\hat{F}_T$ and $\hat{F}_{AC}$ then this method will provide an adequate estimator for F_{AF}. The derivation of an optimal estimator for $\hat{F}_{AF}$ and studying its properties are beyond the scope of this thesis.

As an example of the deconvolution process, assume that a hull coating system has the anti-corrosive empirical cdf and a total paint thickness empirical cdf illustrated in Figure 6.

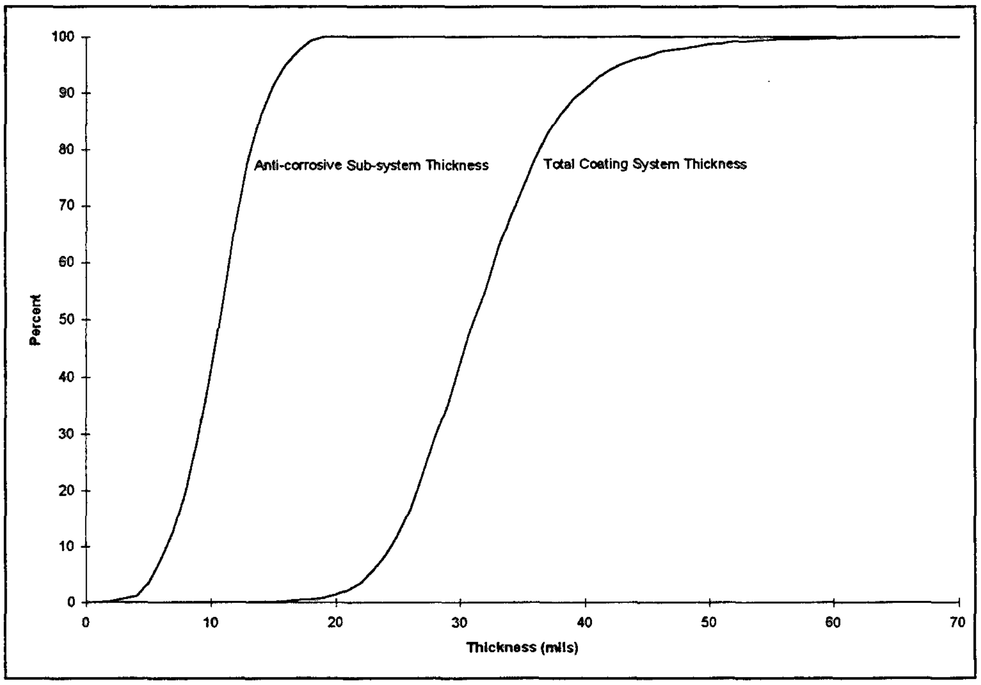

Figure 6. Empirical cdf's of the anti-corrosive and total coating systems.

The distribution of AF is estimated by partitioning [0, 70 mils] into equally spaced values incremented by one mil and solving (2.1.)

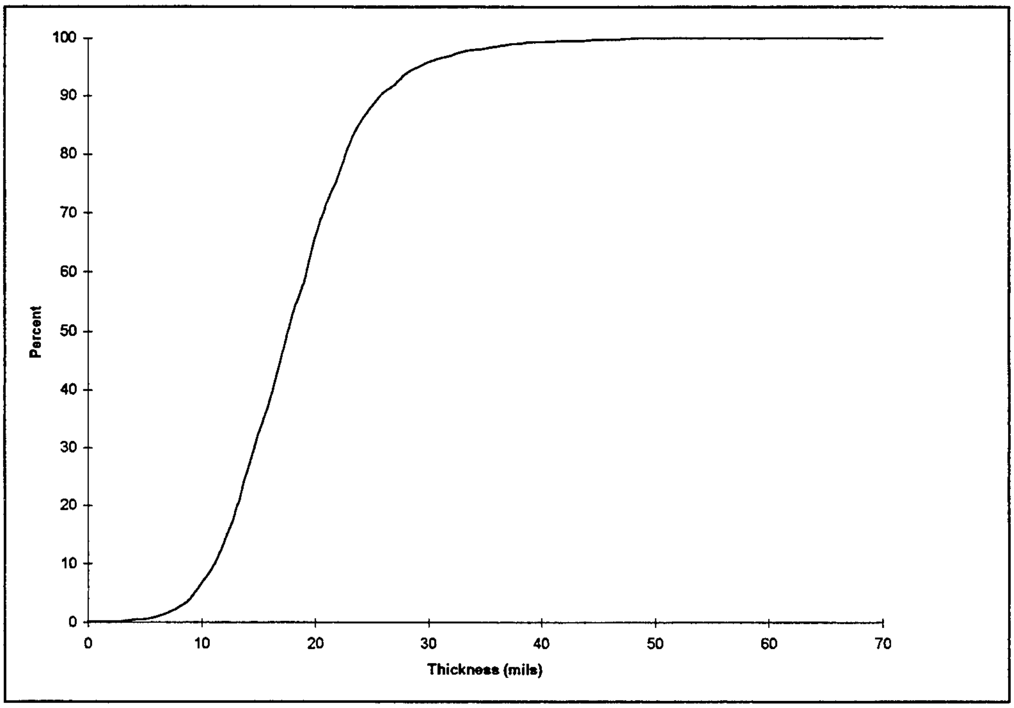

Figure 7. Estimated anti-fouling paint cdf.

The estimated cdf of the anti-fouling thickness distribution, shown in Figure 7, gives a comprehensive view of the entire anti-fouling sub-system. Now, instead of using the total coating system thickness as a "rough" indicator of the thickness distribution of the anti-fouling sub-system, the estimate of the anti-fouling sub-system may be evaluated directly. For example, from Figure 7, approximately ten percent of the anti-fouling sub-system is below the NSTM prescribed thickness of 12 mils. Therefore, a more informed evaluation may be made concerning the application of the anti-fouling sub-system while the ship is still in drydock and more paint may still be applied.

This method of evaluating paint sufficiency provides a tremendous advantage over the current "fixed total thickness" method, since it estimates the actual anti-fouling paint thickness distribution. The current method relies upon the unrealistic assumption that every ship in the US Navy has an identical anti-corrosive paint sub-system. Moreover, since the issue of non-uniform paint application is not adequately addressed in NSTM, the application of the current method becomes vague and open to a wide spectrum of interpretation.

III. EXPLORATORY AND QUALITATIVE ANALYSIS OF COATING WEAR

The two anti-fouling paints currently used by the US Navy were originally designed to reduce fuel costs for merchant ships by curbing marine fouling on their hulls. These paints are designed to work in conjunction with a merchant's rigorous operational tempo and their frequent drydockings. Merchant ships are required by law to frequently drydock for hull maintenance. The US Navy is exempt from these laws, and the length of time between drydocking opportunities is frequently in excess of seven years. The rate and manner of ablation of these anti-fouling paints over long periods of time are unknown. We just now are able to study the effect of wear with the ten years of data collected by PERA(CV.) [Ref. 3]

A. COATING SYSTEM ABLATION

Paint ablation is an extremely slow and continuous process of paint removal, resulting from hydrodynamic abrasion. For the types of anti-fouling paints used by the US Navy, this process maintains a high concentration of anti-fouling toxin on the coating system's surface. The ablation property of the anti-fouling sub-system continuously removes the toxin depleted exterior of a coating system, exposing paint with a higher concentration of toxin to thwart marine growth. An analysis of anti-fouling paint ablation is performed to provide insight into paint ablation characteristics and to ultimately prevent failure due to excessive paint ablation. This analysis uses data taken from coating systems of USS Nimitz (CVN 68) and USS Lincoln (CVN 72.) These data sets include DFT measurements collected by an electronic DFT gauge immediately following coating system application for each ship. DFT measurements were again collected following drydocking four years later for CVN 68 and six years later for CVN 72. Since, no hull treatment procedures were performed on either coating system, wear is caused solely by ablation while at sea.

1. Anti-fouling Paint Ablation Characteristics

To obtain a general overview of the effects of paint ablation over time, Figure 8 depicts the mean and standard deviation of each coating system at the time of paint application and following each ship's respective operational cycle.

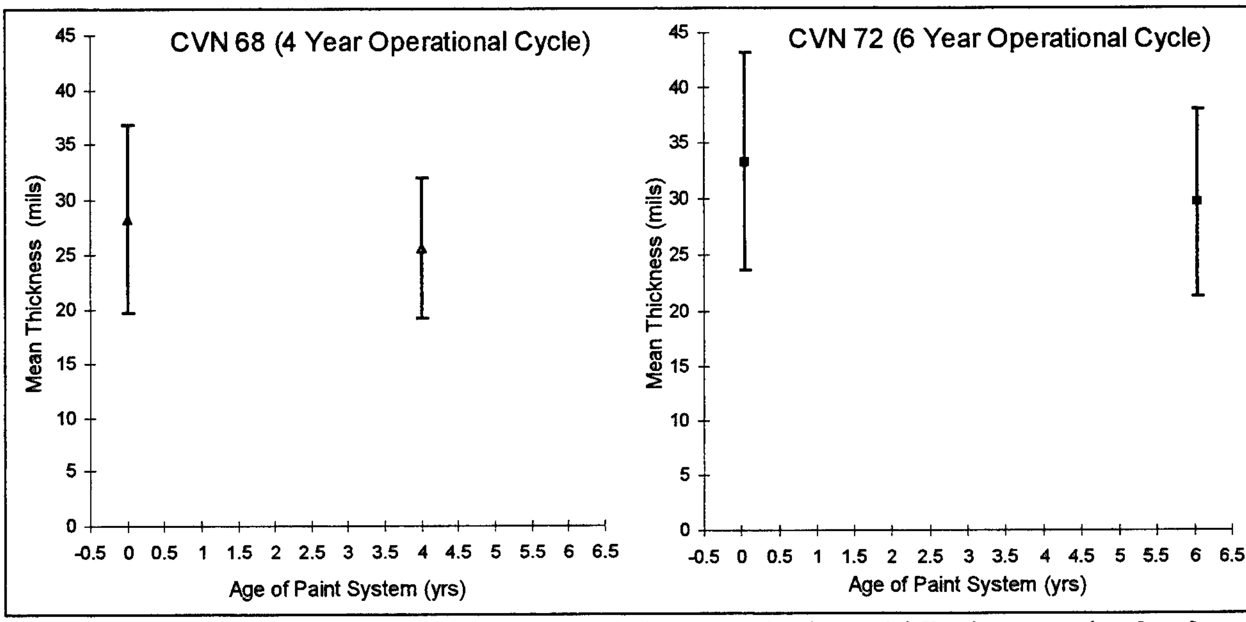

Figure 8. Mean coating thickness ± standard deviation at application and following operational cycle.

During a four year operational cycle, the mean DFT for CVN 68 decreased from 28.20 mils to 25.57 mils, a net loss of 2.63 mils. CVN 72's mean DFT decreased from 33.36 mils to 29.61 mils, a net loss of 3.75 mils. As expected, the hull coating system with the longer operational cycle has a larger decrease in mean DFT, losing nearly 30 percent more paint. Since CVN 72's operational cycle was one-third longer than CVN 68's operational cycle, the net loss of approximately one-third more paint suggests that the rate of paint ablation remains relatively constant over time. Figure 8 also illustrates a reduction in the coating system's standard deviation over time. During CVN 68's four year operational cycle, its coating system's standard deviation decreased by 25 percent from 8.51 to 6.39. Although CVN 72's operational cycle was one-third longer than CVN 68's, its standard deviation decreased by only 13.75 percent from 9.75 to 8.41.

The change in the standard deviation for each coating system suggests that the transformation of the paint thickness distribution is more complex than what would be caused by uniform paint ablation. Figure 9 illustrates the changes to the paint thickness distributions for both paint systems over time.

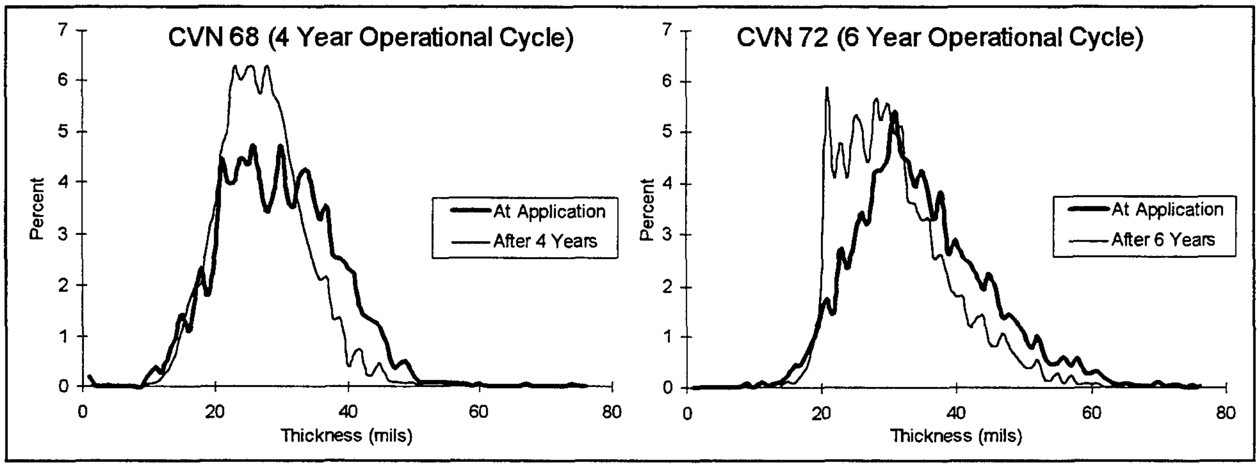

Figure 9. Distribution of coating system thickness before and after an operational cycle.

The shape of the paint thickness distributions for both ships change with wear rather than simply shifting to the left as would be expected if paint ablation were uniform. The heavy right tails of the distribution appear to retract with wear while the left tail of each distribution remains relatively unchanged. This suggests that during the first four to six years, the thicker paint ablates at a faster rate than the thinner paint thicknesses. To illustrate the changes in ablation properties over time, the empirical cdf's, shown in Figure 10, provide a quick yet detailed synopsis of the rate and manner of paint ablation experienced by each coating system.

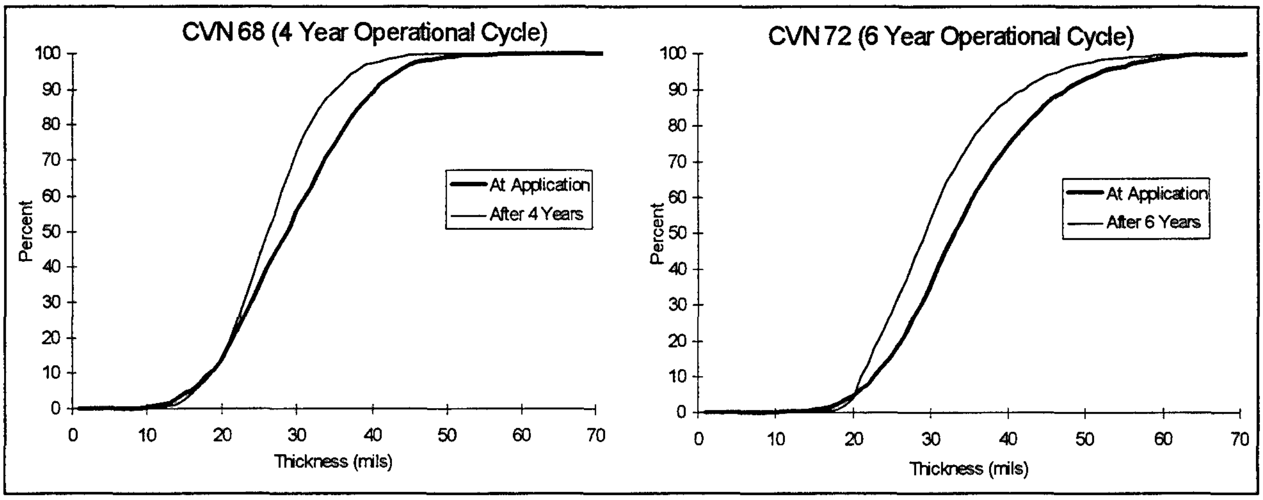

Figure 10. Empirical cdf's of coating system thickness before and after an operational cycle.

From the empirical cdf's in Figure 10, the first quartile of CVN 68's DFT measurements, representing the thinnest one-fourth of the coating system paint, experiences a decrease of only 0.8 mil during the four year operational cycle. In addition, there is negligible change in the thinnest 15 percent of CVN 68's coating system. CVN 72's first quartile decreases during its six year operational cycle from 26.6 mils in 1990 to 23.45 in 1996, three times that of CVN 68's. Moreover, the percent of the left portion of the tail which is "unaffected" drops from 15 percent to only six percent for an operational cycle that is only two years longer.

2. Conjectures and Implications

By assuming that CVN 72's ablation characteristics are consistent with CVN 68's during the first four years of its operational cycle and that ablation is monotone in paint thickness as well as time, several conjectures may be made from a more detailed comparison of the two coating systems. During the beginning of an operational cycle, the thicker paint ablates at a high rate, while the thinnest paint experiences minimal ablation, remaining virtually unaffected by the time at sea. Since areas of thick paint are so widely dispersed, sufficient toxin is released during the ablation of this initial phase to effectively inhibit marine growth over the entire hull. As the operational cycle continues, the rate of ablation for the thickest paint slows considerably, as the rate of ablation for the thinner DFT measurements increases. This shift in ablation rates suggests that a coating system can withstand a short operational cycle with virtually no impact to its

thinnest paint measurements. However, as the operational cycle continues past some critical length of time, the coating system's ablation characteristics change and the thinnest paint becomes subjected to a disproportionate amount of ablation and wears at a faster rate. The two case studies suggest that the thinnest 15-25 percent of a coating system begins rapid ablation immediately following the fourth year of an operational cycle. If this can be confirmed with additional data, the implications of this conjecture are that a ship's coating system can safely persevere for up to a four year operational cycle (with no hull maintenance procedures) with absolutely no impact to the thinnest 15 percent of its coating system. Therefore, as long as at most 15 percent of the coating system at application is below a desired, yet acceptable, coating thickness, there is virtually no chance of an excessive ablation failure during a four year operational cycle. However, for a six year operational cycle (with no hull maintenance procedures,) ablation significantly increases for the smaller paint thicknesses, and only the thinnest six percent of a coating system remains unaffected by the operational cycle. Therefore, only six percent of a coating system may be below the desired, yet still acceptable, coating thickness in order to have minimal probability of an excessive ablation failure during a six year operational cycle. This means that less paint may be required for shorter operational cycles.

B. COATING SYSTEM CLEANING PROCEDURES

Regardless of the condition of a ship's anti-fouling paint system, its underwater hull is extremely susceptible to marine fouling during extended port stays. Since minimal, if any, paint ablation occurs while a ship is stationary for long periods of time, the surface of its coating system becomes depleted of toxin and the coating system loses much of its anti-fouling capabilities. In addition, a ship's hull and propeller frequently become covered with bacteria, pollutants and debris while stationary in stagnant and polluted harbor water. Extended exposure to dirt, oil, and various other types of pollutants produces a slimy film that covers the entire underwater hull coating system. As a result, marine organisms can safely attach themselves to the slimy protective buffer on the hull without being in direct contact with the coating system's anti-fouling paint. Once the underwater hull is fouled, the heavy slime and marine growth must be removed in order to prevent further and accelerated fouling. Frequently, once a ship recommences routine

underway operations, its movement through the water is sufficient to remove light slime and minor marine growth. However, if the degree of marine growth is substantial, an underwater hull cleaning will be required. Indicators of hull fouling include a reduction in ship's speed, a decrease in fuel efficiency, and clogged sea water intakes. If any of these symptoms occur, then an underwater hull inspection is immediately scheduled and the decision whether or not to perform a hull cleaning is made.

1. Description of Hull Cleaning

Hull cleanings are conducted to remove the heavy slime and marine growth from a ship's hull and propellers while ships are between drydockings. The SCAMP Hull Cleaning System, shown in Figure 11, is used exclusively to perform hull cleanings on all US Navy ships. The SCAMP is a diver operated device that attaches itself to the hull of a ship by impeller-produced suction and scrubs the coating system with rotating brushes.

Figure 11. SCAMP Hull Cleaning System.

Divers direct the SCAMP similarly to a self-propelled lawn mower along the bulk of the hull, scrubbing the entire hull coating system. Hard to reach places and the ships propellers are cleaned by hand held rotary brushes.

The relatively inexpensive cost of performing a hull cleaning and rejuvenating a fouled coating system immediately yields several benefits including: improved ship performance and maximum speed, reduced propulsion machinery wear, improved fuel efficiency, improved sonar

performance and a decrease in ship's noise. However, the scrubbing force required to remove advanced marine growth not only removes barnacles and slime, but anti-fouling paint, as well. Prior to 1985, the US Navy used "hard" non-ablative paints, removing only an insignificant amount of paint during a hull cleaning evolution. The anti-fouling paints currently used by the US Navy are much softer than their predecessors and are considerably more vulnerable to the scrubbing of the SCAMP's brushes.

2. Impact of Hull Cleaning Procedures

To evaluate the impact of a hull cleaning on a coating system comprised of ablative, anti-fouling paint, DFT data collected both before and after a single hull cleaning is analyzed. The data set consists of 200 DFT measurements collected by divers using an electronic DFT gauge in a ten foot wide strip along the length of the hull before a hull cleaning. The data includes another 200 DFT measurements collected in the same area immediately following the hull cleaning. Table 3 lists the summary statistics for the data set.

Data Set	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum
Before Hull Cleaning	18.6	31.5	35.45	34.1	41.35	48.2
After Hull Cleaning	18.6	27.9	31.35	30.5	37.6	46.7

Table 3. Summary statistics before and after a hull cleaning.

Although the minimum DFT remain the same for both data sets, the 1st quartile, median and 3rd quartile indicate a substantial change in DFT of 3.6 to 4.1 mils or the equivalent of one prescribed coat of anti-fouling paint. To further illustrate the effects of a hull cleaning, Figure 12 plots the empirical cdf's of an underwater hull coating system before and after a single hull cleaning.

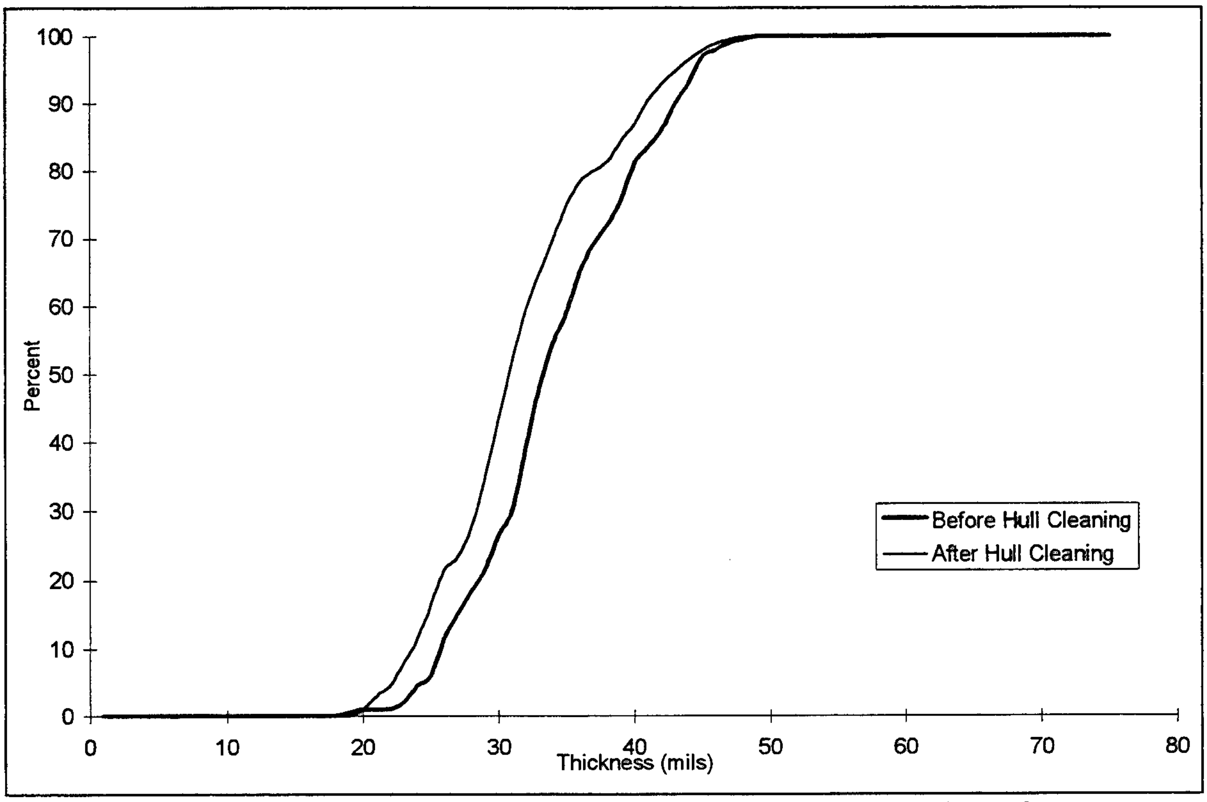

Figure 12. Impact of a hull cleaning upon a coating system's empirical cdf.

With the exception of the largest quantiles, which are of less interest, the difference between the two empirical cdf's is a shift in location of 3.5 to 4.1 mils. This shift indicates uniform paint removal of nearly one coat of anti-fouling paint over most of the coating system.

Figure 13 demonstrates the severity of a single hull cleaning compared to a coating system that has been subjected to six years of operation.

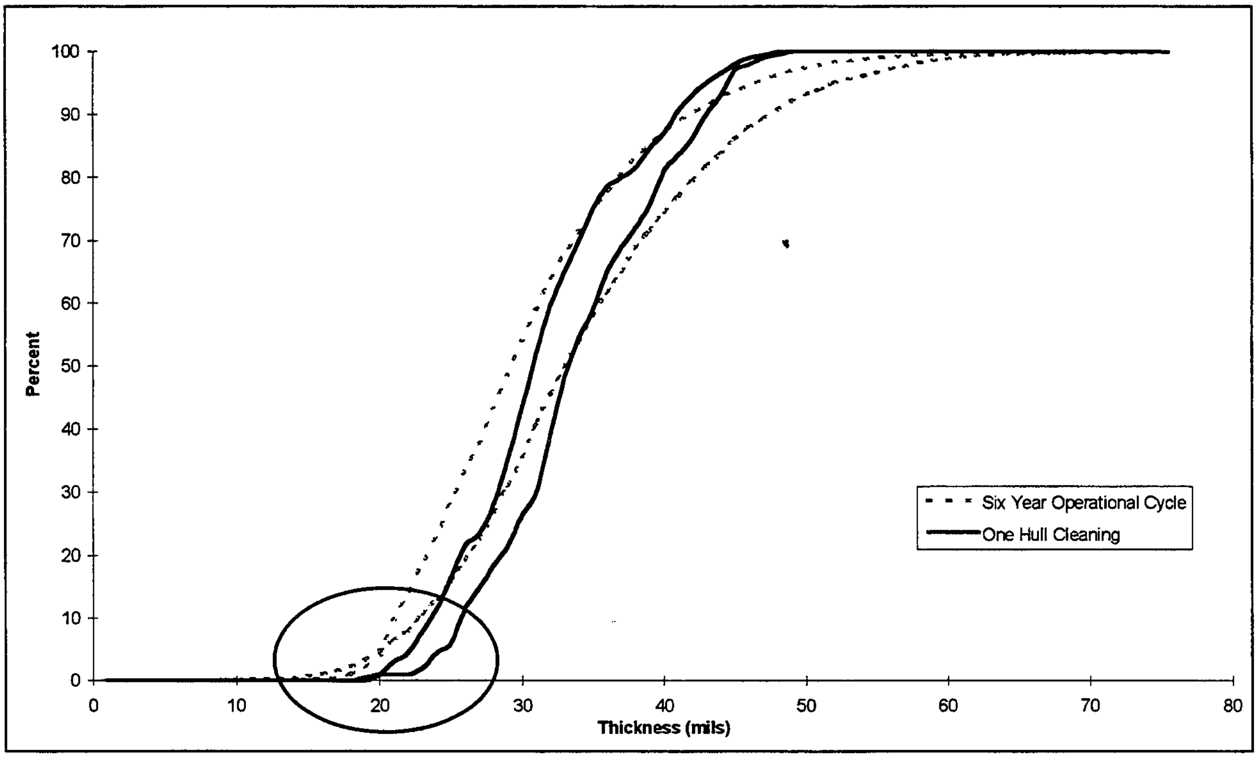

Figure 13. Comparison of the empirical cdf's of paint thickness before and after one hull cleaning to the empirical cdf's of paint thickness before and after a six year operational cycle.

Both the recently cleaned coating system and the six year old coating system have approximately the same average loss in paint thickness, 3.57 mils and 3.75 mils, respectively. However, the wear of the coating systems are considerably different. The six year old coating system experiences severe paint wear in the thickest regions and significantly less wear where the paint is at its thinnest. The recently cleaned coating system has a more uniform paint removal and loses a significant amount of paint from regions of both thick and thin paint. In fact, the thinnest one-fourth of the recently cleaned coating system actually loses more paint than thinnest one-fourth of the six year old coating system. This implies that a hull cleaning has a more adverse effect upon a coating system than six years of paint ablation and exposure to environmental elements while at sea.

3. Impact of Hydro-wash Procedures

Frequently, hull cleaning are required for aircraft carriers just prior to entering drydock for hygienic reasons and to help facilitate coating system inspection and repairs. When a hull cleaning

is not feasible prior to drydocking, a hydro-wash, a high pressure water wash conducted immediately after the ship enters drydock, may be performed. Since hydro-washes can only be performed while a ship is in drydock, few hydro-washes are administered in comparison to the number of hull cleanings that a ship receives. However, like the hull cleaning, some paint is removed during the hydro-wash. To measure the impact of a hydro-wash, Figure 14 contains the empirical cdf's of USS Eisenhower's (CVN 69) distribution of paint thickness immediately before and after a hydro-wash.

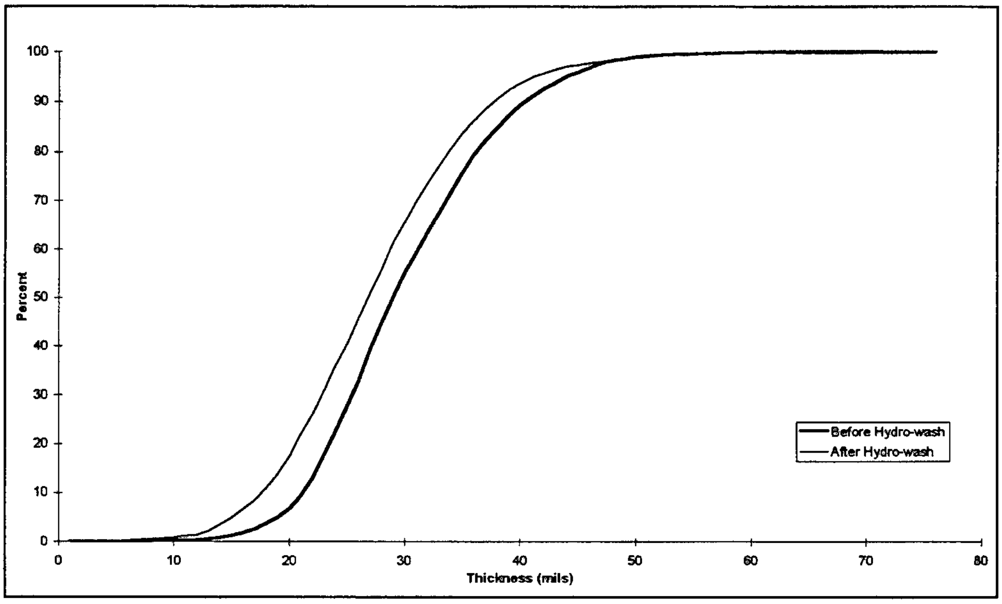

Figure 14. Impact of a hydro-wash upon a coating system's empirical cdf.

The thickness of the coating system decreases from an average of 28.98 mils to an average of 26.35 mils. It decreases 0.94 mils +/- 0.65 mils less on average than with a hull cleaning. Furthermore, the paint removed is approximately uniform over the entire coating system, significantly impacting the coating system's thinnest paint.

4. Discussion

Previously, the severity of a ship's operational and maintenance cycle with respect to its underwater hull coating system was based primarily upon its duration with little or no emphasis to the number and type of hull maintenance procedures performed. The impact of hull cleanings and

hydro-washes is relatively unknown and is assumed to be negligible in comparison to a ship's operational tempo. However, an analysis of the data indicates that this assumption is incorrect. In fact, the data indicate that the impact of a single hull cleaning upon a coating system's thinnest paint is more severe than the ablation of six years at sea. Thus, when deciding how much anti-fouling paint to apply, it is imperative to project the number of times a hull will be cleaned during an operational cycle.

Hull cleanings are sometimes scheduled as a precautionary measure prior to a ship's deployment. Now, with insight into the adverse effects of hull cleanings, it is clear that unnecessary hull cleanings should be eliminated and a limit to the total number of hull cleanings that a ship may receive during a specific operational cycle should be established. By understanding the variables that impact a ship's underwater hull coating system, coating systems may be tailored to persevere specific operational and maintenance cycles to enhance coating system serviceability and "retainability" through multiple operational cycles.

IV. A MODEL FOR COATING SYSTEM WEAR BEHAVIOR

The most pressing and basic question during the paint application process is "Does this coating system possess sufficient anti-fouling paint to adequately endure the ship's projected operational and maintenance cycle?" Any model to predict coating system wear must consider two key elements. First, the model must capture the change of the entire coating system thickness distribution as a function of various hull maintenance procedures and operational cycles. The second requirement is that the model must be able to predict wear for any coating system, regardless of shape of its thickness distribution. As illustrated in Figure 1, coating systems possess very different thickness distributions following paint application. To overcome these two obstacles, we exploit the observation that the change in quantiles of a coating system's thickness before and after both hull maintenance procedures and various observed operational cycle duration is roughly linear. Using change in quantiles as the underlying premise of evaluation gives a concise representation of the entire thickness distribution for any coating system. Moreover, the roughly linear relationship in the changes to the quantiles of a coating systems thickness distribution permits the effective use of a least squares regression to develop a quantitative model for coating system wear.

This chapter develops a mathematical model that quantifies the impact of the duration of an operational cycle, number of hull cleanings and number of hydro-washes upon a coating system's total thickness distribution. The model is based on the empirical cdf's of total coating system thickness of five aircraft carriers measured before and after various combinations of time at sea and hull maintenance procedures. Since the underlying anti-corrosive sub-system is very hard and not subject to wear, the changes in the total coating system predicted by the model actually reflect only the changes in the anti-fouling paint. If the empirical cdf of the anti-corrosive sub-system is measured at application, it and the predicted empirical cdf of the total thickness can be deconvolved, as in Chapter II, to predict the anti-fouling thickness distribution. This chapter includes a detailed description of the model development and a numerical example. For completeness, a discussion on the effect of hull location on ablation is included.

A. COATING SYSTEM ABLATION AND WEAR BEHAVIOR MODEL

Since existing data concerning coating system wear is restricted to a coating system's initial thickness distribution, length of operational cycle, number of hull cleanings received and number of hydro-washes received, the variables of a predictive model will comprise of only these factors. These variables will be considered from the perspective of their impact upon a coatings system's quantiles. Therefore, the ultimate product of the model is the change in thickness of an initial coating system's quantiles for a specific projected operational and maintenance cycle.

1. Modeling the Impact of Operational Cycle Duration

The first variable considered is the impact of a ship's operational cycle. Figure 15 illustrates the change in the quantiles of the total thickness distribution for the coating systems of CVN 68 following a four year operational cycle and CVN 72 following a six year operational cycle.

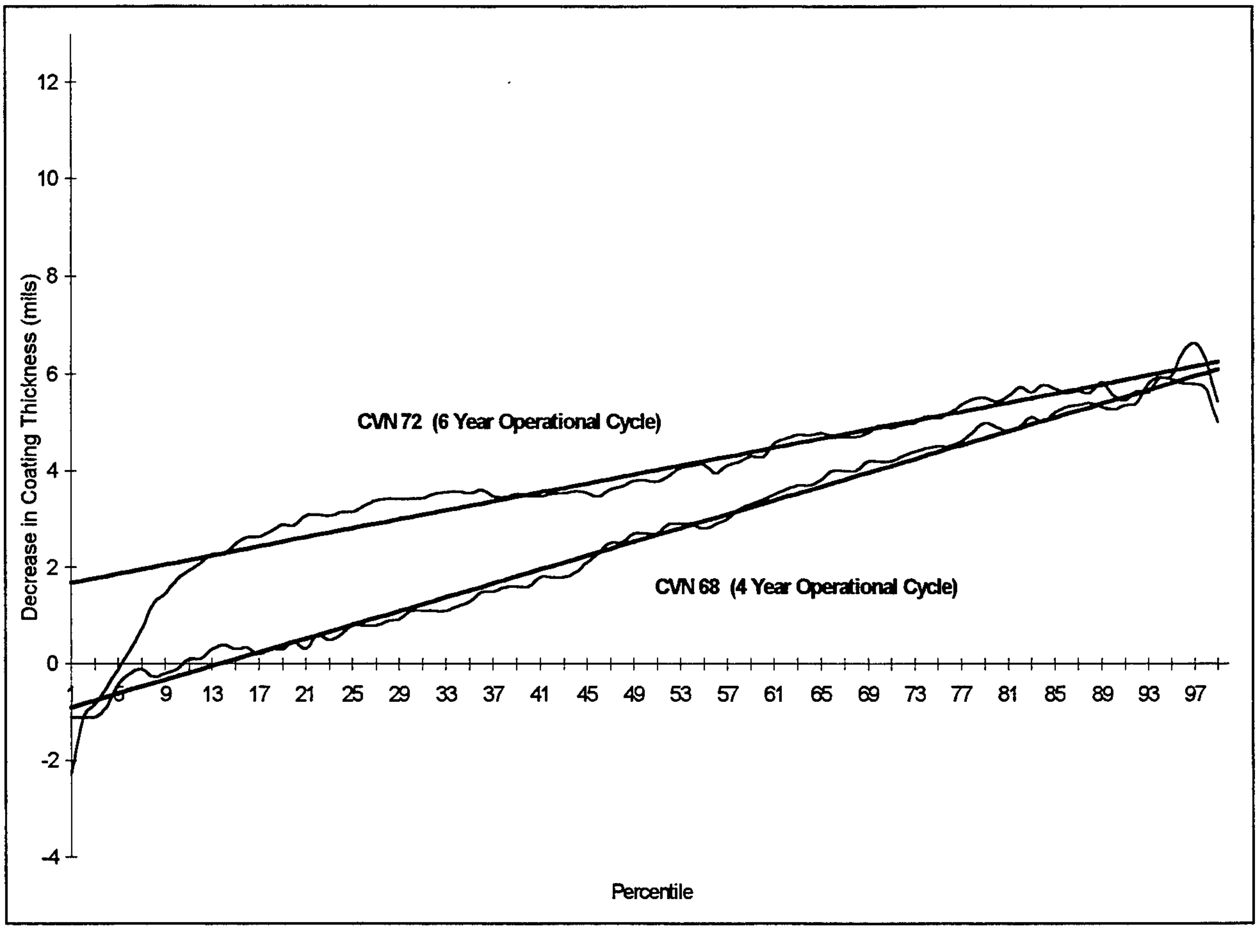

Figure 15. Change in coating system quantiles for a four and six year operational cycle.

Since no hydro-washes or hull cleanings were performed during either ship's operational cycle, changes to both coating system's quantiles are exclusively a product of the length of each ship's respective operational cycle. Figure 15 shows a linear relationship in the change in quantiles of DFT measurements across nearly all percents for both coating systems. With the exception of the smallest percents, the linearly increasing loss of paint is quite pronounced. This confirms the findings presented in Chapter III that a coating system does not exhibit uniform ablation across all coating thicknesses. The negative change in quantile thickness for both coating systems in the smaller percents indicates an increase in DFT for the coating systems' thinnest paint during these two operational cycles. The reason for this behavior is not certain. Since the smallest quantiles represent the "valleys" and "crevices" of a coating system, it is feasible that "dirt" or some other form of debris or oxidation could settle into these crevices. Slight creep or paint swell could be other potential reasons. It is suspected that following application in a "dry" environment, the

anti-fouling paints currently used by the US Navy swell when the ship returns to sea [Ref. 3]. Assuming this is true, the DFT measurements taken while the ship is still in drydock do not reflect the "inflated" thickness of the paint after it becomes "wet." Consequently, sections of the hull coating system where the paint is not experiencing ablation would appear to grow thicker when the ship returns to drydock. This could also explain the non-linearity of CVN 72's change in quantiles below 12 percent. Since the reason for this "increase" in paint thickness for the extremely small quantiles is unknown and we do not have the data to model it adequately, the decrease in quantile is modeled as linear for all percents. This results in a more conservative model.

2. Modeling the Impact of Hull Cleanings

Hull treatment procedures, as shown in the empirical cdf's in Figures 10 and 12, have a significant effect upon the service of a coating system and must be considered, as well. The effects of a hull cleaning and a hydro-wash upon a coating system's quantiles are illustrated in Figure 16.

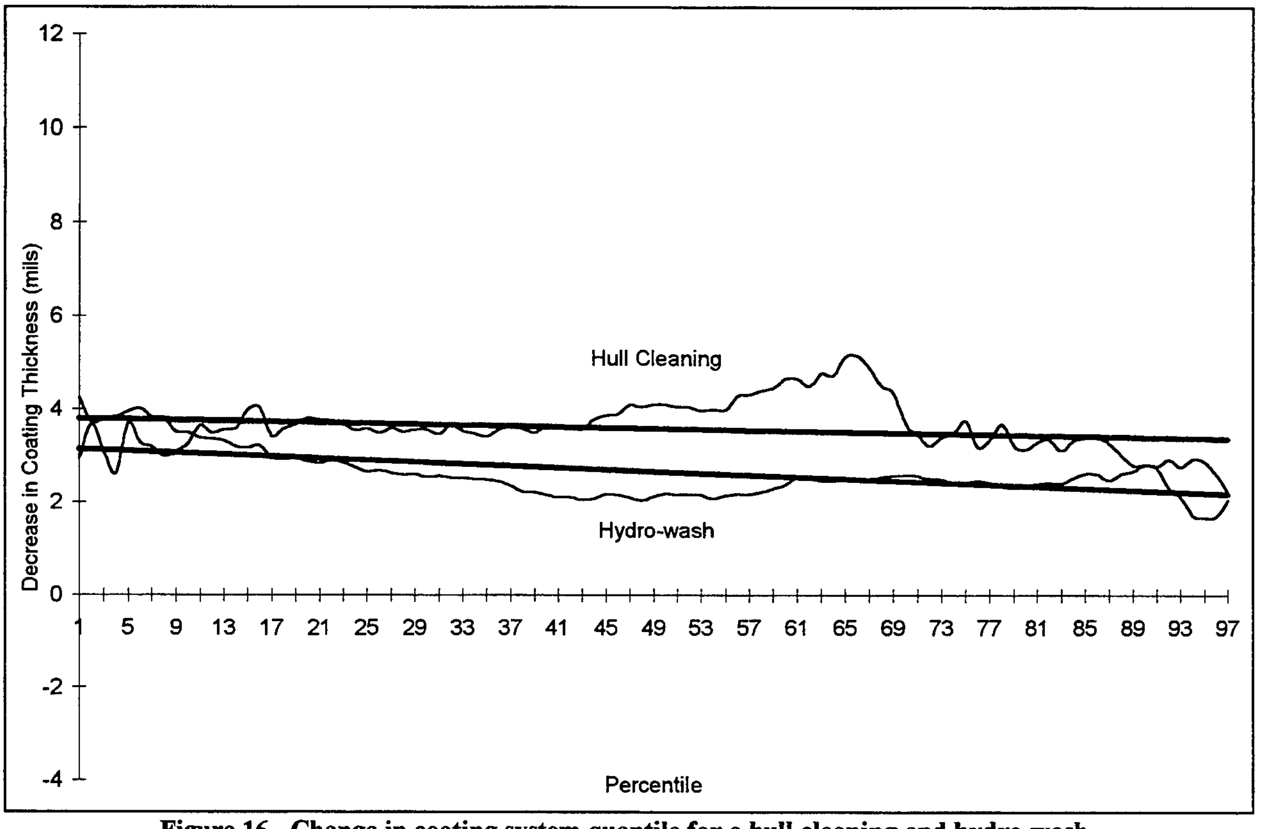

Figure 16. Change in coating system quantile for a hull cleaning and hydro-wash.

As illustrated in Figure 16, the decrease in quantile thickness for both types of hull treatments is more uniform over the entire coating thickness distribution than the aged coating systems in Figure 15. Moreover, the effects of hull treatment procedures produce a more consistent decrease in coating thickness over the entire coating system and can be adequately modeled with a least squares linear fit. Although for this data a hydro-wash removes over one mil of paint less than a hull cleaning, it appears that the hydro-wash may actually cause slightly more wear than the hull cleaning in the thinnest ten percent of paint. This observation needs to confirmed with more data.

3. The Model

Due to the data available, the change in a coating system's quantiles is assumed to be a function of only the number of hull cleanings received, the number of hydro-washes received and the length of a ship's operational cycle. To approximate the change in quantiles over an operational cycle, a least squares fit is computed based on the empirical cdf's of the total coating

system before and after the operational and maintenance cycles of five data sets summarized in Table 4.

Data Set	Duration of Operational Cycle (years)	No. of Hull Cleanings	No. of Hydro-washes
CVN 72	4	0	0
CVN 68	6	0	0
CV 59	0	1	0
CVN 69(a)	0	0	1
CVN 69(b)	8	2	0

Table 4. Data sets used in fitting the model.

The response variable y_p is taken to be the difference in the p^{th} quantile before and after an operational cycle, for p = 10, 11, . . . 90. Consistent with the plots in Figures 14 and 15, y_p is modeled as linear in p for a fixed operational cycle of duration D, with C hull cleanings and W hydro-washes. In addition, to extrapolate the operational cycles not represented by those in Table 4, the variable y_p is modeled as linear in duration, number of hull cleanings and number of hydro-washes. Since the amount of paint removed during a hull cleaning or hydro-wash should not in general depend on what else occurs during the operational cycle, this model appears plausible. On the other hand, it is not known exactly how the duration of an operational cycle effects ablation. The relationship may be more complex than the linear one being used. However, with data for only three different duration lengths, four, six and eight years, a linear approximation is the most sensible. It is also not known whether hull cleanings or hydro-washes affect the amount of subsequent ablation. However, with the minimal amount of data available, these effects, if present, can not be adequately modeled here. This model gives the following least squares approximation for y_p:

$$y_p = -1.8175 + 0.0465p + 0.4616D + 5.3411C + 4.6404W + 0.0021pD - 0.0425pC - 0.0527pW. \quad (4.1)$$

The approximation for y_p for the five operational and maintenance cycles given in Table 5 are plotted in Figures 17 and 18.

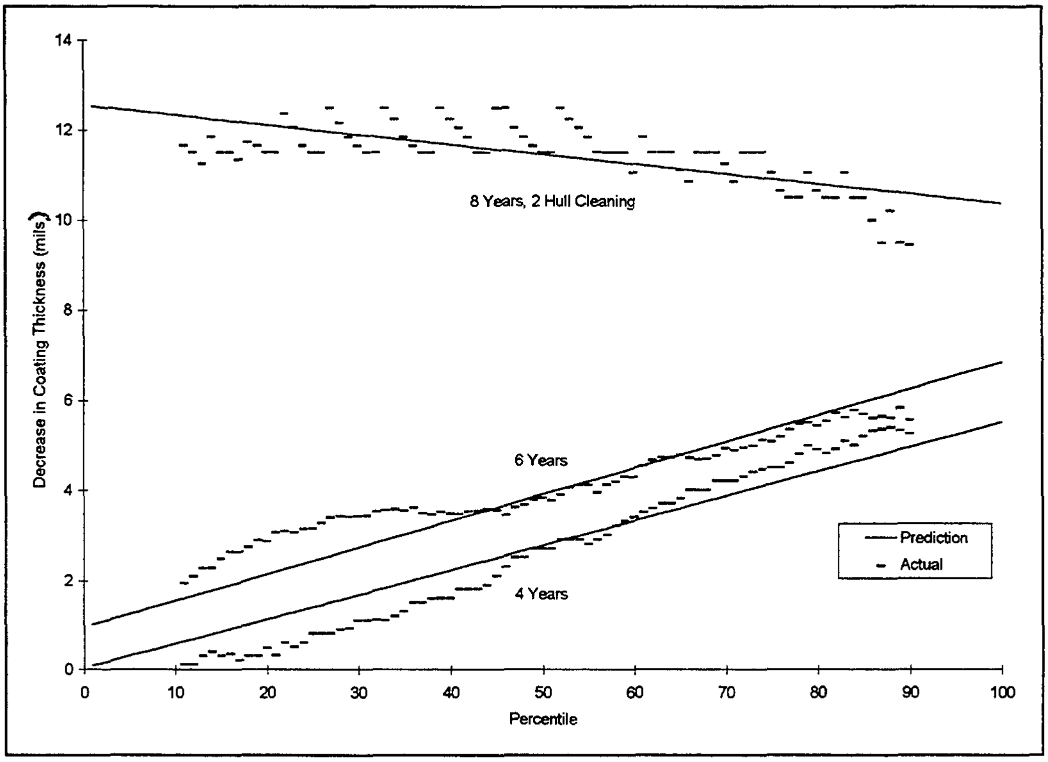

Figure 17. Predicted and actual quantile differences from various operational and maintenance cycles used in model development.

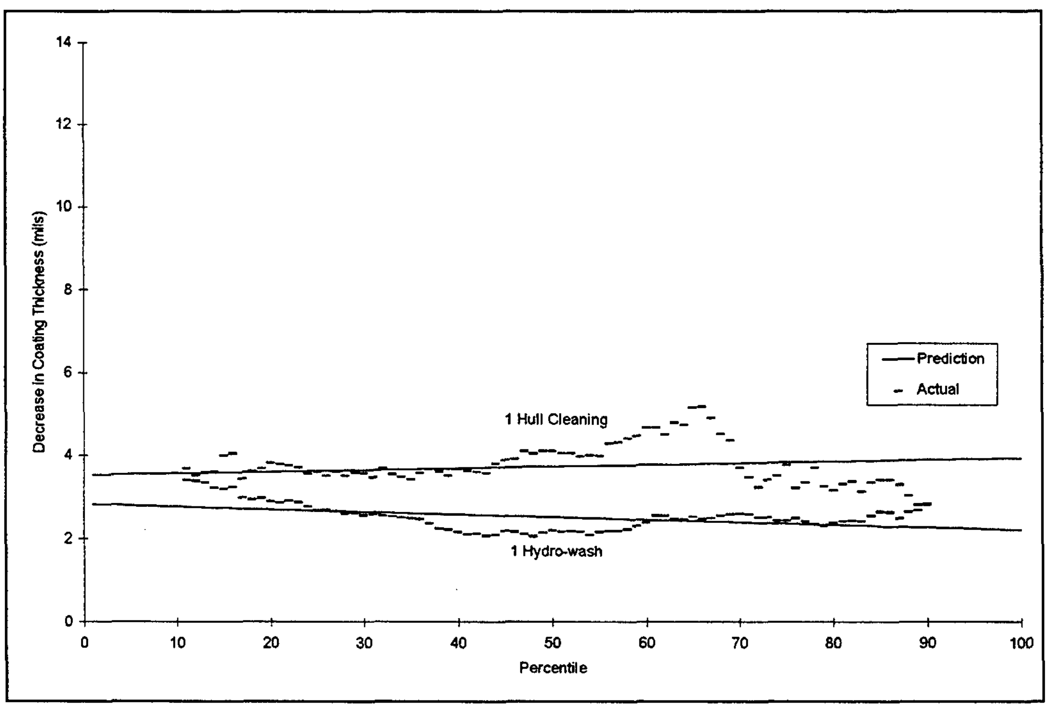

Figure 18. Predicted and actual quantile differences from hull cleaning and hydro-wash procedures used in model development.

Clearly, the assumptions needed for inference based on Normal linear model theory [Ref. 7] in particular independence, are not met by this data. Thus, standard errors are not computed. However, as an indication of fit, this model gives a squared multiple correlation coefficient of 0.983.

An additional pair of data sets from CV 59 was not used in the model development since one of the data sets included DFT measurements from only the bottom portion of the hull. This data encompasses a two year operational cycle with a single hull cleaning. Figure 17 compares the actual empirical cdf of CV 59 before and after a two year period with one hull cleaning to the model's predicted cdf.

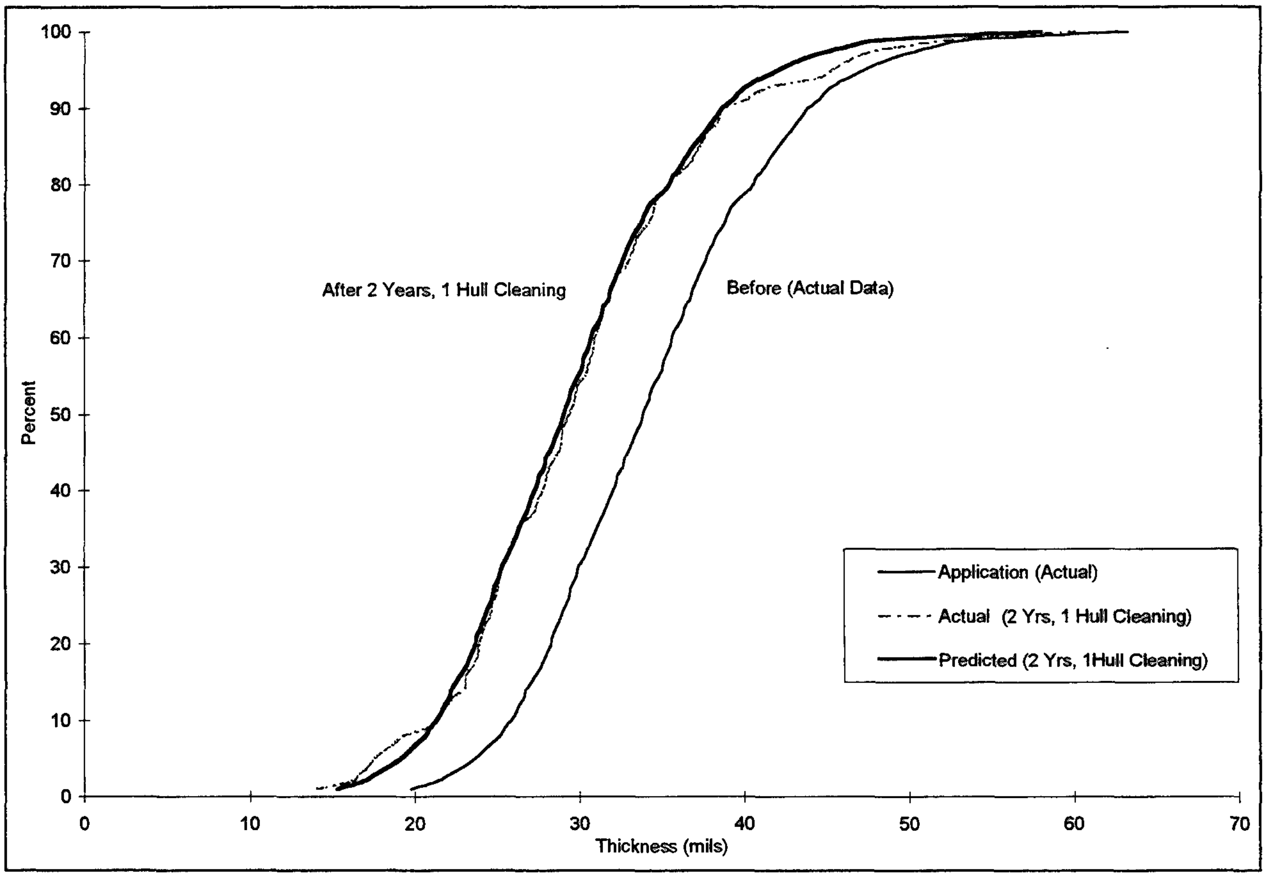

Figure 19. Model Validation--Predicting the coating system distribution from a known data set following a two year and one hull cleaning operational/maintenance cycle.

The model's predicted cdf for coating system thickness is remarkably close to the actual distribution of CV 59's coating system. Since this data set was not used to construct the model

and the fact that CV 59's operational cycle is unlike those in Table 4, then there is a strong indication that the model is effective.

B. AN EXAMPLE

The ultimate goal of this study is to predict how the anti-fouling coating system will wear as a result of a given operational and maintenance cycle. This goal is accomplished in two steps. The model developed in the previous section is used to predict what the coating distribution will be after the ship's projected operational and maintenance cycle. Once the transformation of the coating system thickness distribution has been predicted, the anti-fouling paint thickness distribution is estimated using the de-convolution method described in Chapter II. If the predicted anti-fouling thickness distribution meets a minimum criterion, then it is believed that the coating system can successfully persevere that particular operational/maintenance cycle and still remain in a salvageable condition. If the predicted anti-fouling thickness distribution does not meet the minimum criterion, then one of two courses of action is recommended. The first course of action is to modify the projected operational and maintenance cycle in order to prevent excessive wear and ablation beyond a salvageable condition. This may include omitting a hull cleaning or shortening the operational cycle between drydocking opportunities. The other, more likely, course of action is to simply apply more paint until the predicted anti-fouling thickness distribution following the projected operational and maintenance cycle exceeds the minimum criterion.

For example, assume a ship receives the coating system that has total paint and anti-corrosive paint thickness distributions given in Figure 20 in preparation for a six year operational cycle, anticipating one hull cleaning during the six years. The values used to generate these distributions are given in Appendix A.

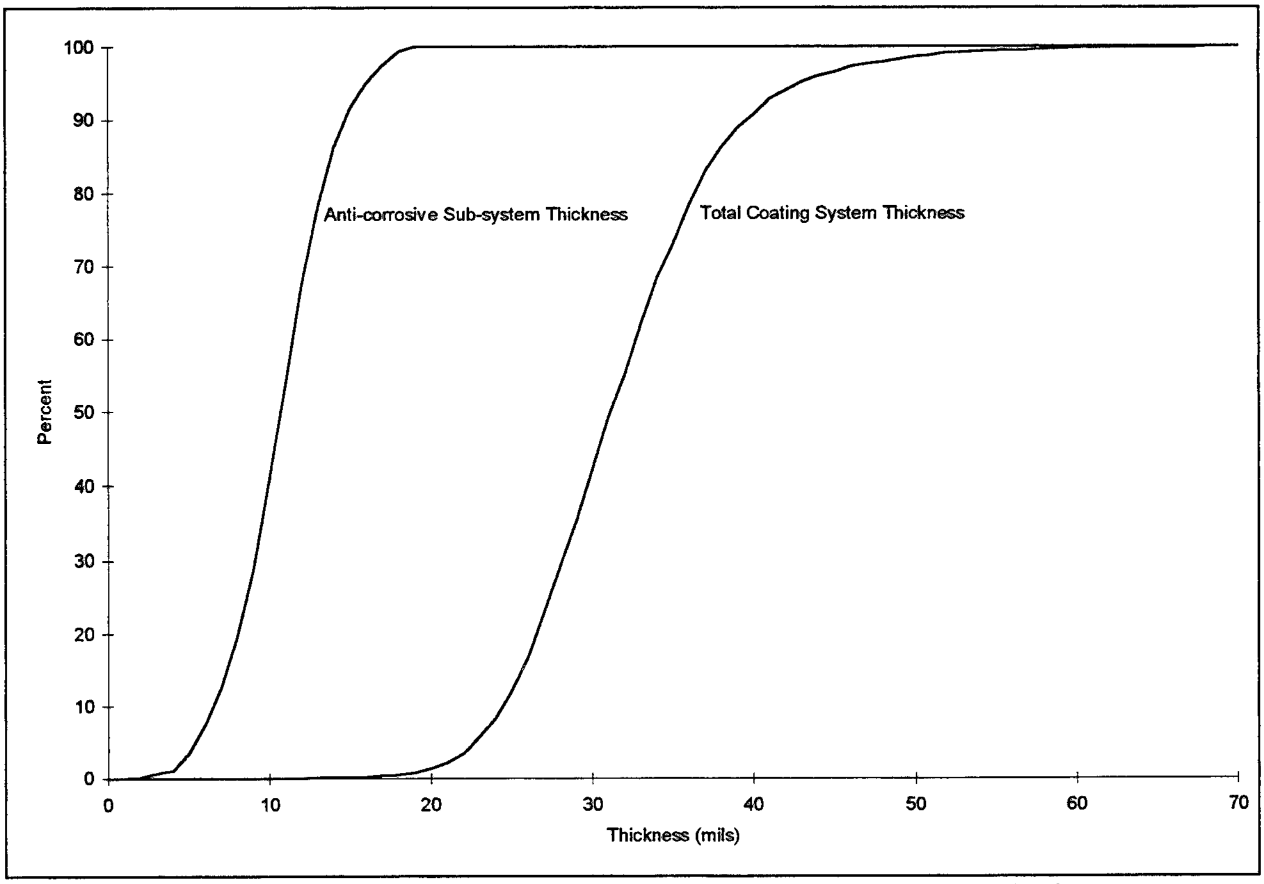

Figure 20. Anti-corrosive and total coating empirical cdf's following application.

Both the anti-corrosive and the total coating system distributions have median thicknesses in excess of their prescribed NSTM thicknesses, 10.66 and 26.72 mils respectively. The change in the quantiles of the total thickness over the operational cycle is approximated by Equation (4.1) with D = 6, C = 1, and W = 0. These along with the distribution of total thickness in Figure 21 are used to predict the distribution of total thickness after wear.

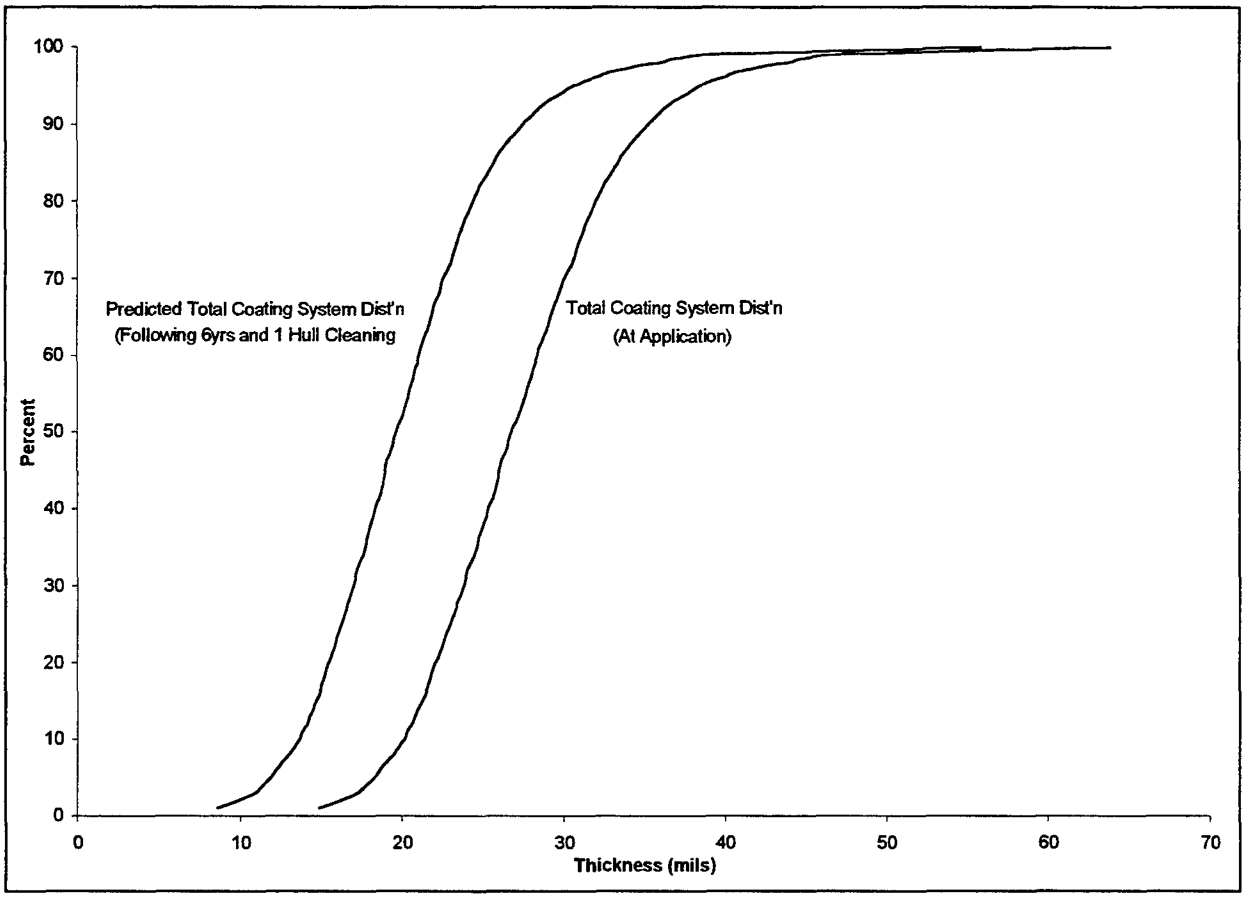

Figure 21. Actual total coating empirical cdf at application and estimated total coating cdf following a projected six year and one hull cleaning operational and maintenance cycle.

This in turn is used to predict the distribution of anti-fouling thickness after wear using the de-convolution method indicated in Chapter II. Here $\hat{F}_T$ is the predicted cdf of total paint thickness and $\hat{F}_{AC}$ is the empirical cdf of anti-corrosive thickness measured immediately following application. The estimated anti-fouling cdf following six years of wear and one hull cleaning is provided in Figure 22.

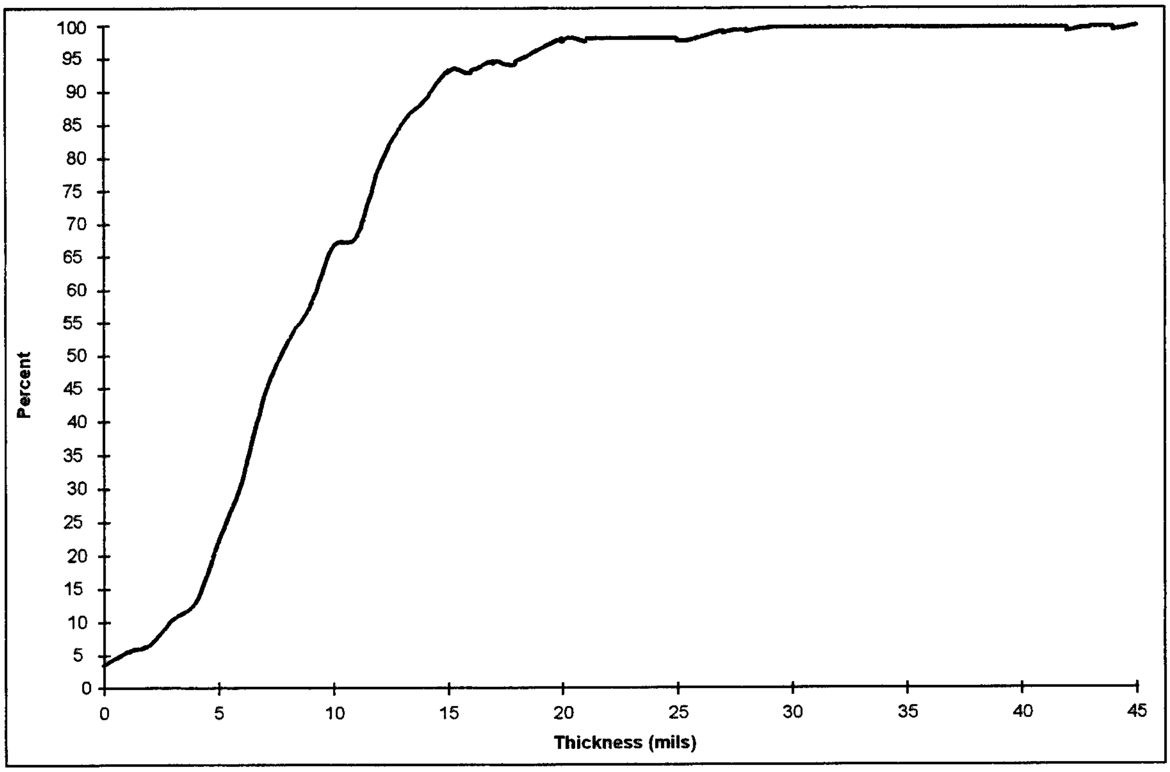

Figure 22. Estimated anti-fouling cdf following the projected six year and one hull cleaning operational and maintenance cycle.

Note that approximately four percent of the underwater coating system is estimated to have absolutely no anti-fouling paint. The lack of anti-fouling paint in these areas will result in accelerated hull fouling and will consequently have an adverse impact upon the ship's performance and fuel expenditures. Moreover, these areas will require very costly and time-consuming inspection and repairs during the ship's next drydocking, and depending upon the dispersion of the "missing" anti-fouling paint, it may actually be more cost effect to completely remove and replace the entire coating system. To ensure that the coating system remains in a serviceable state through its next drydocking opportunity, either the operational cycle must be reduced in duration to only four years, the hull cleaning eliminated, or additional paint must be applied. The more realistic alternative is to simply add additional paint until the coating system "passes" some determined minimum criterion to ensure paint sufficiency throughout the entire operational and maintenance cycle

This approach is a tremendous change to the current policy of applying a standard, prescribed coating system that is completely independent of the ship's anticipated operational and maintenance cycle. Under the present guidelines, little concern would have been given to whether

a coating system with a median thickness larger than the prescribed thickness would adequately persevere a relatively short operational cycle of only six years with a single hull cleaning. Consequently, the current policy places a ship's coating system in risk of wearing beyond a serviceable and "retainable" condition prior to its next drydocking opportunity.

C. EFFECTS OF DFT MEASUREMENT LOCATION

In this analysis, the location on the hull of DFT measurements are not taken into consideration. This information was not recorded for the data sets analyzed in the previous sections. In a drydock environment, it is virtually impossible to define the location of thousands of DFT measurements and to perfectly replicate the survey of DFT measurements following the ship's operational and maintenance cycle. In addition, the degree of variability in paint thickness is so great that a very small area of a few square inches could produce a wide range of DFT measurements. However, it is plausible that both vertical and horizontal location may have an effect on paint ablation rates, due to the hull design and its hydro-dynamic properties. Since paint is not applied uniformly due to the current limitations in paint application, it is also plausible that paint may not be applied consistently over the entire hull, as well. This may be a result of the accessibility of various regions of the hull while the ship is in drydock. Since no comprehensive and detailed study has been performed concerning the impact of hull location upon ablation rates or paint application for aircraft carrier coating systems, a limited analysis is performed here to provide some insight. Only two aircraft carrier data sets exist that include the location for each DFT measurement. Moreover, these data sets were collected following each ship's respective operational and maintenance cycle and no records exist for either coating system immediately following paint application. Thus it is not possible to separate differences in location due to ablation or paint application.

The first data set, from the USS Independence (CV 62,) consists of only the average and standard deviation of 50 unrecorded DFT measurements collected every tenth frame (approximately 60 ft apart) for both the port and starboard side of the front two-thirds of the ship. The data was collected from an eight year old coating system that received no hull maintenance during the eight years. Figure 23 plots the average DFT measurements by frame location.

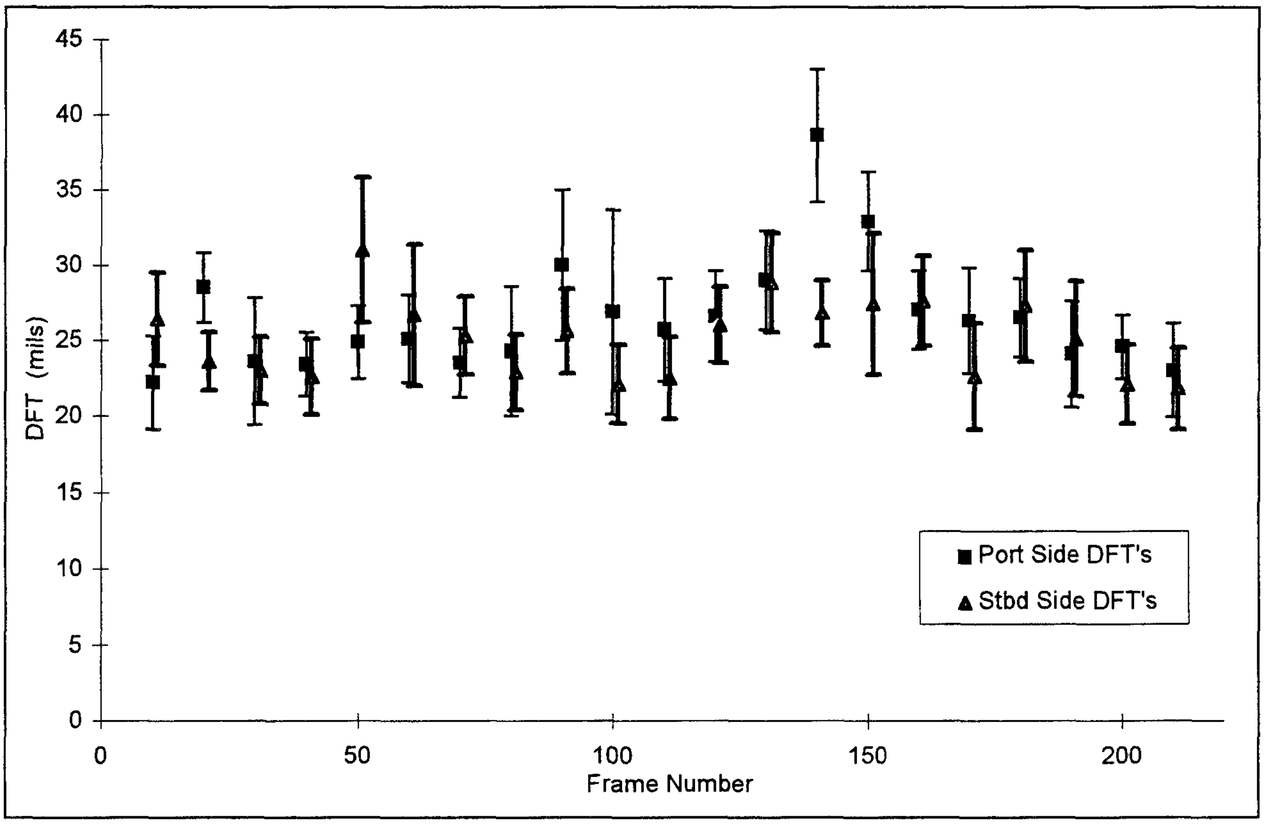

Figure 23. Mean total coating thickness with standard deviations vs. frame number location for the port and starboard sides of the ship's underwater hull.

It is clear that the differences in mean paint thicknesses between location are greater than can be explained by local variation in paint thicknesses. However, there is not enough evidence to support a systematic trend, either increasing or decreasing from front to back on both sides of the ship. Non-parametric tests for trend [Ref. 8] give p-values of 0.0299 and 0.179 for starboard and port sides, respectively. To explore the possibility of any cyclical trends, a runs test is performed on data sets from both the starboard and port sides of the hull. The runs test (p-values 0.768 and .011, respectively) indicates the possibility of a cyclical trend on the port side but not on the starboard side.

The second data, collected from USS Eisenhower's (CVN 69) eight year old coating system, is used to evaluate the effects of vertical location on paint ablation rates. All measurements are taken from the front one-third portion of the hull in three locations: near the waterline, midway down the hull, and at the bottom of the vertical portion of the hull. In Figure 3.2, the averages from the three vertical locations can be seen for both the port and starboard side of the hull.

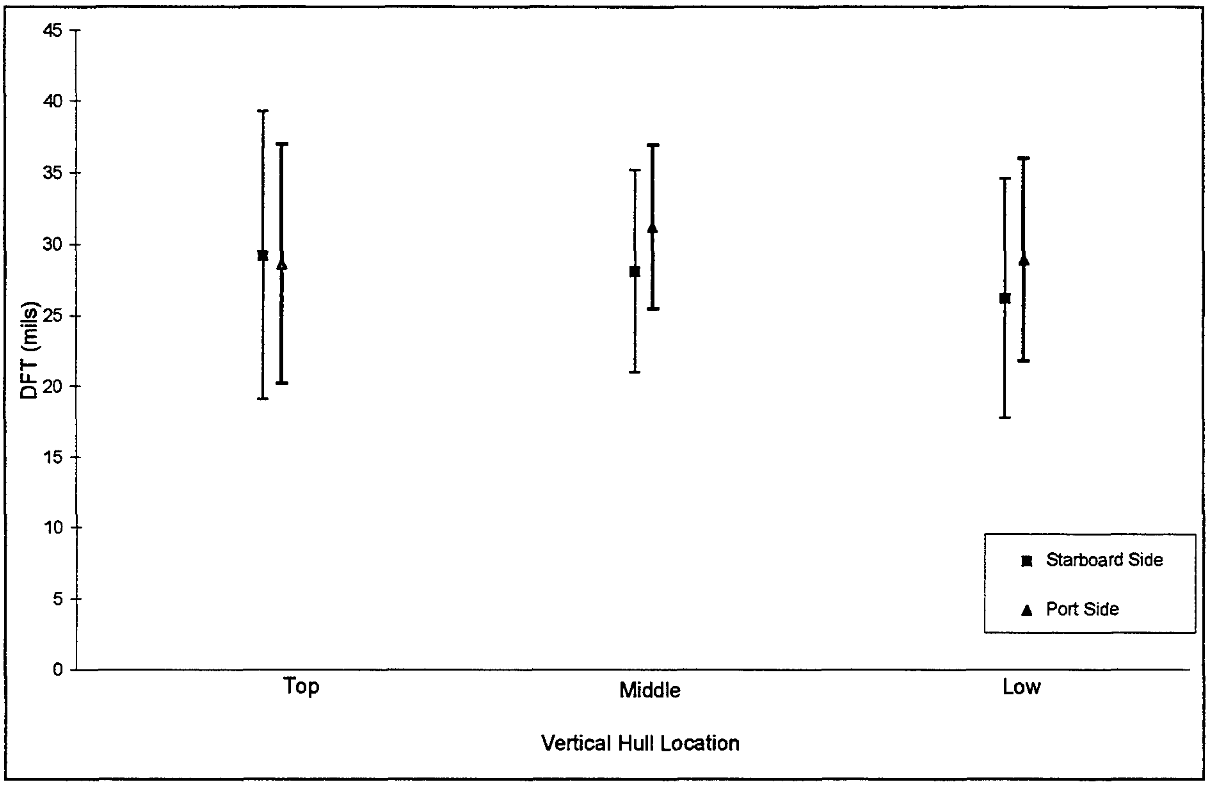

Figure 24. Mean total coating thickness with standard deviation vs. vertical hull location.

Although a two-way analysis of variance with interaction easily rejects the null model of constant mean DFT between the six different hull locations (p-value = 0.000002), the difference between the means are small compared to the variability of thickness at each location. Further, Figure 24 clearly illustrates the absence of any distinct trend or practical difference in mean DFT as a result of vertical hull location.

The analysis of the effects of hull location is not based on a controlled experiment. It is based only upon the measurements taken from CV 62 and CVN 69 for which the initial condition of either hull coating system is not known. Although no conclusive results can be derived from this limited analysis, there is evidence to support the possibility that paint ablation or paint application may vary with hull location. Although the need for a more detailed analysis is obvious, the assumption that ablation characteristics are independent of hull location is consistent with basic principles of fluid dynamic. The hull of a US Navy ship is designed to produce a smooth, laminar flow of water along its surface as the ship moves through the water. Since laminar flow exists along the bulk of the hull, identical hydro-dynamic conditions should theoretically exist for the majority of the coating system, regardless of location. Moreover, it

seems likely that whatever phenomena that would cause an increasing trend on one side of the ship would produce the same effect on the other side, and there is insufficient evidence to support similar trends on both sides.

For the purpose of modeling coating system wear in this thesis, it is assumed that there is no practical difference between ablation rates due to hull location. Moreover, since it is virtually impossible to maintain precise location records for DFT measurements in a drydock environment, location may not be a feasible variable for a predictive paint wear model with current paint measurement techniques.

V. DISCUSSION AND CONCLUSION

As the Fleet maintenance community continues their efforts to extend the intervals between drydocking intervals for aircraft carriers from approximately seven years to twelve years, the demands upon a coating system are significantly increased. Such an extension of a ship's operational cycle requires coating systems to persevere through operational and maintenance cycles more strenuous than previously encountered. To safely meet this heightened operational tempo, improved insight concerning anti-fouling paint wear characteristics is required. By understanding the rate and manner in which a coating system wears, analytical tools, such as predictive models, can be developed to test and determine the outer bounds of an existing coating system's expected service life, and, therefore, reduce the risk of an excessive wear failure.

The purpose of this thesis is to perform both a qualitative and quantitative analysis of the wear characteristics of an aircraft carrier's underwater hull coating system in order to meet the challenges of extended operational cycles. In doing so, a simple, yet potentially useful, model to predict the impact of a ship's projected operational and maintenance cycle upon its underwater hull coating system is developed. The potential benefits of predicting coating system wear and estimating the impact to the anti-fouling paint sub-system are numerous and include considerable cost savings for hull husbandry and improved hull coating system performance. An example of predicting paint wear and estimating anti-fouling sub-system thickness is illustrated to provide an alternative to existing NSTM guidelines and to show the weaknesses of current coating system evaluation techniques.

A. RECOMMENDATIONS FOR EXISTING COATING SYSTEM GUIDELINES

Current US Navy instructions promulgated in NSTM are vague and include numerous implicit assumptions. The three primary assumptions are uniform paint application, uniform coating wear over time, and that a "one size fits all" paint scheme with a total coating system thickness of 24-25 mils may safely endure any feasible operational and maintenance cycle. These assumptions would support the exclusive use of a ship's total coating thickness as a reasonable measure of both anti-corrosive and anti-fouling paint sufficiency. However, this analysis clearly indicates that these assumptions to be grossly incorrect.

A freshly applied coating system possesses an enormous amount of variability in coating system thickness, making the total coating system thickness a potentially misleading indicator of the thickness of the anti-corrosive and anti-fouling sub-systems. Instead, a procedure to evaluate each thickness distribution individually was demonstrated. By measuring the anti-corrosive thickness and estimating the distribution of anti-fouling thickness, a more detailed evaluation of all elements of a coating system may be performed

The second implicit assumption made by NSTM is that a coating system wears uniformly over time. By comparing the change in a coating system's quantile thicknesses as a result of a specific operational cycle, the data indicates non-uniform, yet roughly linear, wear for each quantile. The two hull maintenance procedures discussed, hydro-washes and a hull cleanings, produced a more uniform removal of paint over all coating system thicknesses. A comparison between the severity of wear of a coating system experiencing six years of operation at sea and a coating system experiencing a single hull cleaning revealed that the hull cleaning had more impact upon a coating system than six years of wear. However, this statement is based entirely upon the data collected before and after a single hull cleaning evolution, but it provides sufficient evidence to warrant a more detailed analysis of the impact and requirements of hull cleanings. Presently, the perceived severity of an operational and maintenance cycle is based primarily upon its duration with significantly lesser concern for the projected number of hull maintenance procedures required.

A simple example of a coating system that easily "passes" the common interpretations of NSTM guidelines, yet was shown to have the potential to experience an excessive ablation failure during a typical operational and maintenance cycle, was illustrated. This example clearly shows that NSTM's third assumption that a "one size fits all" paint scheme with an average total coating thickness of 24-25 mils is sufficient to endure any operational and maintenance cycle is incorrect. Although this data was fabricated explicitly to illustrate this shortcoming in NSTM guidelines, as intervals between drydockings are extended the possibility of an excessive ablation failure is not only feasible, but it is very likely given present practices concerning hull maintenance policies.

B. POTENTIAL APPLICATION FOR THE SURFACE FLEET

Although the limited scope of this thesis is intended to serve as a pilot study for further and more detailed analysis as data becomes available, a potentially useful model and coating system evaluation techniques were developed. These analytical tools provide a significant improvement over current NSTM directed practices and are recommended for immediate consideration and implementation to the aircraft carrier maintenance community. Moreover, since all major US Navy ships possess the same underwater hull coating system, these analytical tools may have some benefit for the remaining 320 ships in the US Navy, as well.

The data collected from aircraft carrier underwater hull coating system to "fit" the model should be consistent with the wear characteristics of all surface ships. Since, the impact of hull maintenance procedures are completely independent of the shape or size of the hull that the maintenance is being performed, the impact of hull maintenance should be consistent for all navy ships. The other variable in the paint ablation and wear model is duration of a ship's operational cycle. Implicit in this variable is the very reasonable assumption that all aircraft carriers possess similar operational tempo's over long periods of time. However, this assumption may not hold true among different types of surface ships. Typically aircraft carriers have a more strenuous operational tempt than other ship types, such as a frigate or dock landing ship. Therefore, the amount of ablation for aircraft carriers is expected to be worse than other ships. Consequently, the paint ablation and wear model could be used to provide a "conservative" estimate of coating system wear for all non-aircraft carrier ships. Currently no analytical tools are in existence to assist in the evaluation of non-aircraft carrier hull coating systems.

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APPENDIX A. COATING THICKNESS DATA USED IN EXAMPLE

Percentile	Anti-corrosive Thickness (mils)	Total Coating Thickness (mils)	Percentile	Anti-corrosive Thickness (mils)	Total Coating Thickness (mils)
1	3.709269	14.872314	51	10.73113	26.939485
2	4.419203	16.184816	52	10.80993	27.171276
3	4.780869	17.271725	53	10.90397	27.323
4	5.094067	17.75538	54	10.99669	27.5046
5	5.480217	18.27548	55	11.07498	27.631045
6	5.711103	18.627076	56	11.15667	27.749248
7	5.912384	19.020254	57	11.22349	27.930597
8	6.141546	19.44322	58	11.29042	28.03524
9	6.429287	19.799885	59	11.36737	28.2095
10	6.578734	20.1121	60	11.43938	28.3533
11	6.773767	20.306761	61	11.49671	28.454898
12	6.897172	20.607868	62	11.57995	28.653876
13	7.070014	20.7782	63	11.66101	28.83222
14	7.233821	20.991064	64	11.74493	29.022048
15	7.365856	21.1892	65	11.80728	29.17175
16	7.514065	21.440936	66	11.89063	29.308352
17	7.641391	21.591824	67	11.96619	29.457672
18	7.772879	21.75092	68	12.05035	29.67638
19	7.916648	21.873111	69	12.13671	29.820845
20	8.035429	22.0623	70	12.22453	29.972
21	8.146208	22.285408	71	12.31516	30.236771
22	8.258892	22.441572	72	12.39877	30.477876
23	8.356299	22.59533	73	12.47338	30.631415
24	8.471476	22.735236	74	12.58098	30.762968
25	8.580812	22.94005	75	12.70125	30.937
26	8.689815	23.11468	76	12.79106	31.107904
27	8.789573	23.303304	77	12.87311	31.329822
28	8.888548	23.3965	78	12.96979	31.528
29	8.985275	23.605377	79	13.09267	31.774301
30	9.082621	23.78108	80	13.19188	31.9645
31	9.17204	23.907258	81	13.32732	32.191815
32	9.266445	24.034808	82	13.43555	32.430592
33	9.372441	24.22188	83	13.57321	32.734545
34	9.45964	24.468844	84	13.69572	33.014504
35	9.543883	24.607675	85	13.82939	33.339615
36	9.623788	24.710096	86	13.96154	33.583728
37	9.690336	24.837584	87	14.13361	33.955116
38	9.764432	24.98752	88	14.29576	34.33244
39	9.84769	25.170298	89	14.44705	34.815518
40	9.92272	25.29308	90	14.6691	35.242
41	9.98431	25.465179	91	14.90128	35.69448
42	10.07483	25.674132	92	15.13313	36.206896
43	10.15854	25.795915	93	15.38301	36.82148
44	10.25312	25.91106	94	15.68491	37.683412
45	10.32634	25.988675	95	15.99478	38.42801
46	10.3956	26.108932	96	16.35011	39.758788
47	10.45804	26.305571	97	16.81564	41.1249
48	10.51566	26.48288	98	17.30538	43.77556
49	10.60051	26.571952	99	17.73214	46.684029
50	10.66574	26.7299	100	18.40784	63.779

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